DECISION SUPPORT SYSTEM FOR THE SELECTION OF STRUCTURAL FRAME MATERIAL TO ACHIEVE SUSTAINABILITY AND CONSTRUCTABILITY

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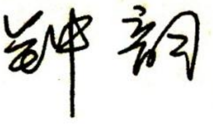
DECLARATION

I hereby declare that the thesis is my original work and it has been written by me in its entirety. I have duly acknowledged all the sources of information which have been used in the thesis.

This thesis has also not been submitted for any degree in any university previously.



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SUMMARY

The role played by the construction industry is a significant one. It contributes to national development and affects economic growth. Its activities also have an impact on the environment. Due to an increased awareness of sustainable development, the construction industry is now presented with the challenges of reducing material consumption, energy consumption and CO_2 emissions, as well as other environmental issues. In addition, the Singapore government has launched a constructability appraisal system and a productivity enhancement scheme to encourage the construction industry to improve constructability. One of the goals of any business concern has always been to raise profitability. However, with the added pressure to reduce the environmental impact of business activities, economic gains should no longer be the only driving factor behind the decision making of an enterprise. Herein lies the challenge to achieve the right balance among environmental performance (EN), constructable performance (CP) and economic performance (EC). There is a clear need to establish the connection between these three aspects.

This study aims to investigate and compare the economic sustainability, environmental sustainability and constructability performance of two structural frame materials for buildings in Singapore - the structural steel (SS) frame and reinforced concrete (RC) frame. The study develops and tests a decision support system that will aid the selection of structural frame material to achieve optimal economic sustainability, environmental sustainability and constructability for building projects. To establish such a decision support system, a holistic framework is built in the form of a decision hierarchy tree to show the factors that affect decision making when the structural frame material of a building is being selected. The framework is underpinned by the theory of the firm, the rational choice theory and the social responsibility theory as well as the concepts of sustainability and constructability.

The choice of research method is the survey. The data was collected through face-to-face interviews using a structured questionnaire. In total, 39 completed questionnaires were gathered from experts with extensive experience in the selection of structural frame materials. From the statistical analysis, the comparative result between SS and RC were drawn based on the three categories of economic performance, environmental performance and constructability performance. Under economic performance, SS buildings incur higher structural costs (EC1), maintenance costs (EC2) and non-construction costs (EC3), but provide higher additional incomes (EC5) than RC. In terms of environmental performance, SS buildings perform better in material consumption (EN1), CO_2 emission (EN2) and water consumption (EN3). Noise pollution is similar for both materials. As for constructability performance, SS projects have more labor saving (CP1), higher construction speed (CP2) and better construction quality (CP3) than RC. Construction safety performance is similar for both systems.

Based on the framework, the decision hierarchy tree was refined by removing those criteria and attributes which had similar performance or been identified as not significantly important in the selection of structural frame material. The Decision Support System for Selection of Structural Material (DSSSSM) was established using the Multi-Attribute Value Technique (MAVT). To make the DSSSSM helpful for users who do not have a deep knowledge of alternative structural frames, this study offers a defined weighting system and defined ratings based on the survey results. Users input the information of those attributes of which they have the estimated performance value. Defined weights are employed when users are not sure about their own priorities, and defined ratings are adopted for those attributes whose performance value users are unable to provide. In order to validate this system, the information on two RC projects and two SS projects were fed into this system to check whether the frame recommended by the DSSSSM was consistent with the actual choice made by experts. The results showed that this system is robust and is of practical use.

This study showed that the industry needs to integrally consider economic goal, environmental goal and constructible goal when selecting structural frame material to achieve a higher level of sustainability and constructability in Singapore. It is recommended that engineers and decision makers use the DSSSSM developed and validated in this study to help them select a structural frame for the building project in a more scientific and sustainable way.

Keywords: decision making, economic sustainability, environmental

sustainability, constructability, structural frame.

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ABBREVIATIONS

AIA	American Institute of Architects
AHP	Analytic hierarchy process
BCA	Building and Construction Authority
BDAS	Buildable Design Appraisal System
BRE	Building Research Establishment
BREEAM	Building Research Establishment Environmental Assessment Method
BSI	British Standard Institution
CAS	Constructability Appraisal System
CIB	Conseil International du Bâtiment (in French), International Council for Building (in English)
CII	The Construction Industry Institute
CIIA	Construction Industry Institute Australia
CIRIA	Construction Industry Research and Information Association
CSR	Corporate Social Responsibility
CWC	Canada Wood Council
DSSSSM	Decision Support System for Selection of Structural Material
GBI	Green Building Initiative
GDP	Gross Domestic Product
GFA	Gross Floor Area
GHG	Greenhouse Gases
GM	Green Mark
HDB	Housing and Development Board
IISI	International Iron and Steel Institute
IMCSD	Inter-Ministerial Committee on Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
IRR	Internal Rate of Return
ISO	International Standardization Organization
LCA	Life Cycle Analysis
LCC	Life Cycle Costing
LCI	Life-Cycle Inventories
LEED	Leader in Energy and Environmental Design
MAVT	Multi-Attribute Value Technique
MCDA	Multi-Criteria Decision-Making
MCDM	Multi criteria decision making
MODM	Multiple Objective Decision Making
NEA	National Environment Agency

NPV	Net Present Value
NRMCA	U.S. National Ready Mixed Concrete Association
OECD	Organization for Economic Co-operation and Development
RC	Reinforced Concrete
ROI	Return of Investment
SEC	Singapore Environment Council
SGLS	Singapore Green Labeling Scheme
SS	Structural Steel
UNFCCC	United Nations Framework Convention on Climate Change
USGBC	United States Green Building Council
WCED	World Commission on Environment and Development
WSA	World Steel Association

CHAPTER 1 Introduction

1.1 Background

1.1.1 Environmental issues recognition

The way the world has used global natural resources in the past has placed a tremendous strain on the environment -- depleting our natural resources, polluting the environment, warming the earth, raising sea levels, and endangering our biodiversity. Climate change has become the inevitable result of our past actions. As a result of global warming, the global average sea level has risen at an average rate of 1.8 mm/year since 1960 and at 3.1 mm/year since 1993 (IPCC, 2007). This has considerable impact on future development. Furthermore, millions of people have been exposed to natural hazards, including weather-related disasters that take lives, damage infrastructure and natural resources, and disrupt economic activities (Pelling et al, 2004).

A widely accepted cause of global warming is increasing greenhouse gas (GHG) emissions, which come from both natural and man-made sources. However, human activity is believed to be the most significant source of emissions, mainly from energy consumption (such as petrol, gas, oil and diesel) and clearing forests. According to the assessment report from the 4th Intergovernmental Panel on Climate Change (IPCC, 2006), 76% of the world's energy-related carbon dioxide (CO_2) emissions come from cities through transportation, industrial activities, as well as building and construction-related developmental activities.

Sustainable development has always been a key consideration for the development of Singapore. Growing and developing the city in an efficient, clean and green way by utilizing less resources; generating less waste; reducing pollution to the environment; and preserving greenery, waterways and natural heritage, are the goals of the Sustainable Development Blueprint as set out by the Inter-Ministerial Committee on Sustainable Development (IMCSD).

The building sector is the largest source of GHG emissions around the globe. The American Institute of Architects (AIA, 2007) reported that nearly 50% of all GHG emissions came from buildings and their construction process, for example, the energy used in the production of materials, transportation of materials from production factories to construction sites, as well as energy consumed in the operation stage. This means that global recognition of sustainability might bring considerable changes to the construction industry. The construction industry and its associated companies need to be well prepared for increased pressures in the physical, regulatory and competitive aspects of their operations.

Building is the result of combining different materials via a number of complex processes. Calkins (2009) stated that the construction materials industry have begun to work towards sustainability. In the construction industry, two of the main components, concrete and steel, are considered as materials with high embodied energy due to the complexity of the materials and large amount of processes required. It is possible to minimize environmental impact by the appropriate selection of structural materials.

1.1.2 Recognition of constructability issues

Constructability issues have been recognized by many construction industry institutes since the 1980s, who have made appeals for easier construction. In Singapore, the progressive tightening on the supply of foreign workers and an increasing demand for better quality make it necessary for the construction industry to adopt labor-efficient designs and use more pre-assembled products. A key measure to achieving them is the introduction of government regulations under the Building Control Act to require building designs to fulfil a Minimum Buildability Score. Singapore has pioneered a method of quantifying buildability based on a scheme known as the Buildable Design Appraisal System (BDAS) since 2001. It consists of a Structural System (Max. 50 points), a Wall System (Max. 40 points), other Buildable Design Features (Max. 10 points), and bonus points. As the biggest part of the BDAS score, the structural system should be designed and constructed in an optimal fashion to maximize constructability.

The Singapore Building and Construction Authority (BCA) expanded the buildability legislative framework beyond the design stage to downstream stages by issuing the Constructability Appraisal System (CAS). The CAS is a means to measure the potential impact of downstream construction methods and technologies on the productivity at the worksite (BCA, 2011b). This means that builders are required to adopt more labor-efficient construction methods. To encourage the building industry to adapt to the upcoming policy changes, the Government has set aside $250 million for the construction sector to work towards higher productivity and to build capability.

A key measure to improve constructability and productivity is to select structural building materials in a scientific way because the construction speed, labor-saving, and other associated performance vary depending on the structural materials used (Booth, 1999).

1.2 Problem statement

Following the global trend towards sustainability, a scientific decision support systemis needed because the traditional budget-oriented selection process is no longer completely suitable for its purpose. However, the development of such a system is a problem because current models are not specific with regards to structural material selection.

Most of the green building assessment tools such as Building Research Establishment Environmental Assessment Method (BREEAM), Leader in Energy and Environmental Design (LEED) and Singapore's local Green Mark (GM) Scheme are applied to evaluate the environmental performance of a whole building from the life cycle perspective. For all of these tools, all of the complicated information is required to be input when using the rating system. This might restrict engineers from a specific area (such as structural engineers) from the use of these systems due to their having insufficient information.

Furthermore, a particular structural material corresponds to particular design regulations and construction processes. The constructability is diversified by the choice of a variety of structural materials. Since 30% - 40% of the total points of these systems (refer to 2.4.2) are related to structure, one possible result could be that using one material may achieve higher points, which makes it the optimized option, but the overall constructability performance may not be good. This means that decision-making process might be biased if it is made only by relying on the current rating systems.

Thus, a sustainable decision support system for structural material selection is an urgent task especially since the construction industry is currently popular for investment.

1.3 Research objectives

The research objectives are:

- to study the economic sustainability, environmental sustainability, and constructability performance of RC frame;
- to investigate the economic sustainability, environmental sustainability, and constructability performance of SS frame;
- to compare the economic sustainability, environmental sustainability, and constructability performance of the two frames; and
- to develop and test a decision support system for selection of structural frame material to achieve optimal economic sustainability, environmental sustainability, and constructability.

1.4 Knowledge gaps

1.4.1 *Current models for the selection of structural materials are not sufficient.*

When making decisions in selecting structural materials, the traditional model of economic analysis is usually utilized by calculating the Net Present Value (NPV), Internal Rate of Return (IRR), and Return of Investment (ROI). However, recognition of the need to incorporate environmental sustainability and constructability requires decision makers to consider these two dimensions while seeking to attain profit goals at the same time.

The most popular assessment tools for environmentally sustainable buildings such as BREEAM (BRE, 2009), LEED (USGBC, 2009c) and even Singapore's Green Mark (BCA, 2009) have provided a comprehensive environmental portfolio for the evaluation of environmental impact. However, those tools do not include financial considerations in their evaluation framework (Ding, 2008). This may contradict the ultimate principle of development, as financial returns are fundamental to all projects. A project may be environmentally sound but very expensive to build and maintain. This study argues that environmental issues and financial considerations should go hand in hand as different parts of the evaluation framework.

Although considerable work has been done to develop an integrated model for material selection, thus far, the models developed have been unsuccessful in establishing a link between economic sustainability, environmental sustainability and constructability. For example, Castro-Lacouture et al.(2008) and Paya-Zaforteza et al. (2009) developed their models for selecting structural materials by integrating environmental and cost goals. However, constructability criteria are absent. Elnimeiri and Gupta (2008) and Giudice et al. (2005) developed their models for selecting structural materials by integrating the environmental and constructability requirements but did not consider economic factors. Sirisalee et al. (2004) developed their model for selecting structural materials by integrating the cost and constructability goal but excluded environmental factors.

Thus, there currently is no model that synthetically assesses the economic sustainability, environmental sustainability and constructability performance for structural material selection between RC and SS.

1.4.2 It is not known whether a steel framed building is more economically sustainable than a RC framed building in Singapore.

To many firms, the main objective of a business is to make profit, which is also used as a criterion of decision-making (Appleby, 1994). Although steel framed housing is popular in the US (20%), UK, Japan (40%), and Australia (Zhang, 2008), steel building is not preferred in Singapore for two reasons.

One is that Singapore does not suffer from earthquake. In countries that are in earth quake zone, steel frames are preferred for super high rise buildings. This is because if RC frames are used, the size of columns and beams would be exceeding large to have seismic resistance when the height of building is more than 100 meters. In Singapore, the structural costs of RC framed buildings might not increase dramatically when the building is taller. Therefore, the advantage of cost saving by using SS frame is not applicable in Singapore. Another reason might be that consultants and contractors in Singapore do not intend to take risks in a new area, which they are not familiar with – in this case, steel buildings.

The Singapore Housing and Development Board (HDB) reported that using steel instead of concrete to construct HDB lifts core achieved 20% cost savings (Sim, 2007). Moreover, many economic benefits brought by steel buildings have been identified, such as additional useable area, longer life span(Liu, 2007), and more feasible space (Booth, 1999). People started to reconsider the economic performance of the two kinds of buildings after that. However, there is no studies reported the economic performance of using SS and RC for building structural material in Singapore.

1.4.3 It is not known unknown whether steel framed building is more environmental sustainable than RC framed building in Singapore.

Efforts have been made to compare the environmental impact of steel versus RC buildings. Conflicting results were found when comparing the results produced by the two materials in different countries.

Some researchers found that waste gas and embodied CO_2 emission produced by RC buildings were more than those produced by steel buildings (CWC, 1997; Guggemos & Horvath, 2005; Lin, 2003), while Peyroteo et al. (2007)

reported the opposite results. In addition, Eaton and Amato (1998) stated that there is no significant difference in terms of embodied CO_2 emission produced by the two materials. There has been no research conducted to compare the CO_2 emission associated with the two frames in Singapore.

Furthermore, Liew (2007) pointed out that other advantages of steel construction should be taken into consideration when evaluating the environmental impact of that material. For example, steel can be 100% recycled by the end of life. This should be considered when comparing the environmental impact of the two structural materials.

1.4.4 It is not known unknown whether steel framed building is more constructable than RC framed building in Singapore.

Steel framed buildings have the advantages of faster construction (Langdon et al., 2002; Liew, 2007; Sim, 2007), easier transportation (Liew, 2007), high construction quality (Liew, 2007), good mechanical performance (Zhang, 2008), and mature construction methods (Zhou, 2005). However, there were only one study reported that SS buildings have advantages of faster construction and less labour consumption in Singapore. The rest studies reported the results of other counties.

1.5 Hypotheses

Based on the literature review, following hypotheses are proposed by this study.

Hypothesis 1- decision making on structural material selection is integrally affected by the material's performance in economic sustainability, environmental sustainability, and constructability.

Hypothesis 2 - Economic performance (EC) associated with structural materials is affected by structural costs (EC1), maintenance costs (EC2), non-construction costs (EC3), end of life costs (EC4) and additional incomes (EC5).

- H2.1 – RC frame has lower structural costs than SS frame.

- H2.2 – RC frame has lower maintenance costs than SS frame.
- H2.3 – RC frame has lower financial costs than SS frame.
- H2.4 – RC frame has higher end of life costs than SS frame.
- H2.5 – RC frame has lower additional income than SS frame.

Hypothesis 3- environmental performance (EN) associated with structural materials is affected by material consumption (EN1), CO_2 emission (EN2), water consumption (EN3), and noise (EN4).

- H3.1 - RC frame has higher material consumption than SS frame.
- H3.2 - RC frame has higher CO_2 emission during construction than SS frame.
- H3.3 - RC frame has higher water consumption than SS frame during construction.
- H3.4 - RC frame produces more noise than SS frame during construction.

Hypothesis 4: The selection of structural materials affects constructability performance (CP) from the aspects of labor saving (CP1), construction speed (CP2), construction safety (CP3) and construction quality (CP4).

- H4.1 - SS frame requires less labor than RC frame.
- H4.2 - SS frame has faster construction speed than RC frame.
- H4.3 - SS frame is safer to construct than RC frame.
- H4.4 - SS frame has higher construction quality than RC frame.

1.6 Scope of the study

This research is conducted in the context of building structural materials at the project level in Singapore because building construction is the most significant sector of construction industry in Singapore as the demand is 65% of the total construction demand (BCA, 2011c).

This study focuses on the building structural frame material selection between *RC* and *SS*. RC, SS, and wood are the most common building structural materials. In Singapore, it is not necessary to consider wood as a structural material as regulations do not allow. Therefore, wood is excluded in this study, and attention is taken on RC and steel.

This study tests that the decision making on selection of structural materials is affected by economic sustainability performance, environmental sustainability performance and constructability performance. This study does not dig further to investigate the correlation between the economic performance, environment performance and constructability.

Since time value and return period are affected by many factors other than structural frame materials such as developers' marketing strategies, changes of loan interest rate, delays. This study does not consider time value and return period so that the influences by those factors which are not related to structural frame materials could be minimized.

The investigation on the performance of SS framed and RC framed projects is not only based on site activities but also off-site activities. For example, a prefabricated item included cost of resources, labor consumption and recycling rate on and off site.

This study focused on the economic performance, the environmental performance, and constructability performance of the two frames. The investigation did not delve further into details such as the specific construction methods, concrete types and steel strengths.

Almost all the steel and cement used in Singapore is imported from different countries. As transportation cost/data was determined by the distance of imported country to Singapore, this study does not take into account the transportation distance and the places of steel and cement imported from because it was too tedious to trace which country the steel and cement were manufactured in.

The contractual payment mechanisms were not considered in this study because the payment from clients to contractor of most construction projects in Singapore is by lump sum. With the Security of Payment Act in place, it is expected that payments were not late, and paid in full. Other project characteristics such as presence of disputes cost and schedule overruns were not investigated as they were outside the scope of this study.

The power tariff in Singapore is the same throughout the country, and therefore the study did not look into different power sources. As Singapore is not situated in an earth quake zone, it is assumed that the buildings generally have conventional concrete and steel strengths.

1.7 Research strategy

The research strategy is shown in Figure1.1.

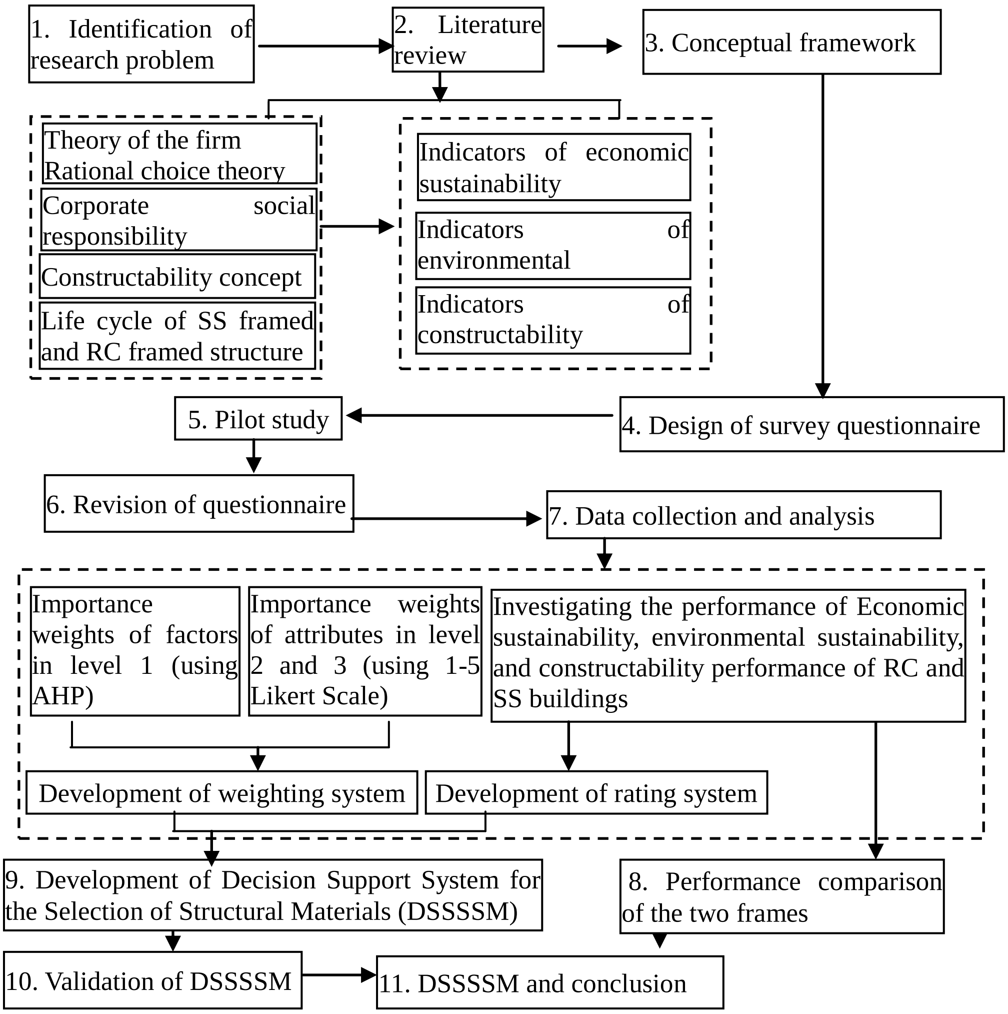


Figure 1.1 Research strategy

Following the identification of research problems (step 1), literature review (step 2) was conducted to form the conceptual framework (step 3) of this study, as well as the questionnaire (step 4). After refining the questionnaire (step 6) from pilot studies (step 5), data collection (step 7) on the performance of the two frames and importance of attributes was conducted. Following statistical analysis, the performance of the two frames was compared (Step 8) to test those sub-hypotheses under H2 to H4 (see Section 4.5). Those data were also used to develop the decision support system for the selection of structural materials (step9) using multi-attributes value technique (MAVT). Validation of the DSSSSM (step 10) is conducted before making the conclusions and recommendations (step 11).

1.8 Structure of the thesis

This report is organized into eight chapters:

Chapter One is an introductory chapter which presents the background, research problems, knowledge gap, and objectives of this research. This chapter also states the scope of the study, which can influence the research methodology, data collection, and data analysis.

Chapter Two presents a review of the literature on the concept of sustainable development and its application in material selection, mainly focusing on the economic and environmental aspects. The evaluation methodologies are explained as well. More importantly, the applicability of the sustainable design philosophy in the structural material selection is identified in this chapter. Beyond the sustainable concept, constructability concept and its application in material selection are explained in this chapter.

Chapter Three describes the background of the structural materials (RC and steel) that this research focuses on, including the process of production, transportation, the design requirements and construction process. Factors that affect the economic sustainability, environmental sustainability, and constructability of SS frame and RC frame are identified.

Chapter Four provides the theory background and the conceptual framework of this study.

Chapter Five covers the research methodology and operational measureables. Followed by the conceptual framework which is provided in Chapter Four, the research methodology of this study is described in this chapter, including data collection and data analysis methods.

Chapter Six reports the statistical analysis results of the importance of factors, criteria and attributes identified in the framework. The statistical description of the performance of RC framed and SS framed buildings are given in the form of box plot chart. Simultaneously, the statistical comparative results of the performance of the two frames are provided. The discussion on those results has been given in this chapter as well.

Chapter Seven presents how the DSSSSM was established. This includes the processes and methods of establishment of weighting system, rating system and aggregation. After the DSSSSM is constructed, the DSSSSM and how to apply the DSSSSM are explained. The DSSSSM validation method and results are provided in this chapter.

Chapter Eight covers the summary, main findings and validation of hypothesis of this study. Followed by the conclusion and recommendation to the future study, the contribution and limitation of this study are explained.

In addition, questionnaires used to collect data for this study and the DSSSSM are provided in the appendixes.

CHAPTER 2 Sustainability and constructability

2.1 Introduction

This chapter reviews the literature on economic sustainability, environmental sustainability and constructability. The evaluation methods and indicators of economic sustainability and environmental sustainability for buildings are reviewed. In addition, the concept and indicators of constructability are reviewed.

The link between sustainable development and structural materials used in a building is first reviewed. Thereafter, how structural elements affect economic sustainability, environmental sustainability and constructability are reviewed.

2.2 Sustainability

2.2.1 Sustainability -- History and principles

Meadows et al. (1972) first gave warning about the conflict between development and environment with a report entitled "*Limits of Growth*" to the club of Rome when the oil crisis happened. It was not taken very seriously at that time.

The first clear statement regarding the human race's responsibility to protect and improve the environment is the "Declaration of the Human Environment". It was adopted at the United Nations Conference on the Human Environment held in Stockholm, Sweden, in 1972.

Sustainability was first defined by Lester Brown (1981), a well-known American environmentalist, who was for many years the head of the Worldwatch Institute. In "Building a Sustainable Society", he defined a sustainable society as one that is able to satisfy its needs without diminishing the chances of future generations.

In 1987, the well-known concept of sustainable development was presented in the Brundtland Report by the UN World Commission on Environment and Development (WCED), headed by the former Prime Minister of Norway, Gro

Bruntland. He adopted Brown's definition, referring to sustainable development as: development that meets the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987). While this definition is widely cited, there are divergent views in academic and policy circles on the concept and how to apply it in practice (Banuri et al., 2001; Cocklin, 1995; Pezzoli, 1997; Robinson and Herbert, 2001).

The importance of maintaining a balance between environmental conservation and economic growth in order to make development a sustainable process was once again clarified at the UN Conference on Environment and Development in 1992. And participating nations signed the UN Framework Convention on Climate Change (UNFCCC).

In recent years, sustainability has been represented by a set of triangular concepts (Kajikama, 2008), which involves a comprehensive and integrated approach to *economic, social, and environmental* processes (IPCC, 2007, p.693) (Kastenhofer and Rammel, 2005). Similarly, the triple-bottom-line or P3 (People, Prosperity, and the Planet) model (Zimmermann et al., 2005) has gained popularity. Discourses on sustainable development, however, have focused primarily on the environmental and economic dimensions. The importance of social, political, and cultural factors is only now getting more recognition. Integration is essential in order to articulate development trajectories that are sustainable, including addressing the climate change problem.

2.2.2 Sustainable construction, sustainable design and building structural materials selection

The sustainable development movement has been evolving worldwide for almost two decades. As a subset of sustainable development, sustainable construction (Kibert, 2008) is of great importance because half of the total raw materials extracted from the planet is used by construction and more than half of the waste we produce comes from this sector (Mourão, 2007).

In 1994, the Conseil International du Batiment (CIB) defined the goal of sustainable construction as "…creating and operating a healthy built environment based on resource efficiency and ecological design" (cited by Kibert, 2008, p.9). The CIB articulated Seven Principles of Sustainable Construction, which would ideally inform decision making during each phase of design and construction. The Seven Principles of Sustainable Construction (CIB, 2004) are :

- Reducing resource consumption
- Reuse resources
- Use recyclable resources
- Protection from toxic substances
- Apply life-cycle costing
- Focus on quality.

It implies that the issues of resource-conscious design are central to sustainable construction, which ultimately aims to minimize natural resource consumption and the resulting impact on ecological systems.

The key to creating an ecological or sustainable building is the ability of the design team to understand and apply the concept of sustainability. The definition of ecological design is given by Van Der Ryn and Cowen (1996) as the intentional shaping of matter, energy, and process to meet a perceived end or desire.

Some would expand this concept of ecological design to an even broader concept, sustainable design, which is defined as the "conception and realization of *ecologically, economically, and ethically responsible* expression as part of the evolving matrix of nature" (cited by Kibert, 2008, p.119). These principles are commonly known as the Hannover Principles, which are listed as follows:

- Insist on the rights of humanity and nature to coexist
- Recognize interdependence
- Respect relationships between spirit and matter
- Accept responsibility for the consequences of design
- Create objects of long-term value.

The role of construction in achieving sustainable development involves a dilemma (Carpenter, 2001). The construction process is regarded as a set of activities that harness nature, and consume energy and resources to service human beings. In the current process, more materials and resources are consumed than nature can supply. On the other hand, construction activities are essential to satisfy the demands of increasing populations and developing economies. Issues of sustainability should be incorporated in structural material selection by integrated reconsideration of the relationships between environment, construction and sustainable development.

When using those principles in the construction sector, it was found that the key problem facing sustainable design is a lack of knowledge, experience, and understanding as to how to apply the concept of sustainability to design (Kibert, 2008). An even deeper flaw is that building professionals have little or no background or education in ecology; hence any application of so-called sustainable design is likely to be shallow and perhaps even trivial. Another problem is that an enormous legacy of machine-oriented design is in place, in the form of buildings and infrastructure; and the industrial products comprising buildings are still being created based on concepts, design approaches and processes that have their roots in the industrial revolution.

2.3 Economic Sustainability and Structural materials selection

2.3.1 Economic Sustainability

Economic growth is regarded as one of the most important targets in the long history of the development of human society because it is tightly connected with the stability of the society and people's living conditions. Pursuing maximum profits is the only aim of a company and the individuals involved. However, indefinite growth is impossible to sustain, if it relies on the depletion of global resources. It is inequitable if it involves gains for some at the expense of others (Carpenter, 2001). The growth rate is restrained by the capacity of other resources, including, but not limited to, natural resources.

Many researchers have explained economic sustainability. According to Repetto (1986), the core idea of sustainability is that current decisions should not impair the prospects for maintaining or improving future living standards. This implies that our economic systems should be managed so that we can live off the dividends of our resources. Therefore societies or economies should be developed at a certain rate that is decided by the capacity of the natural environment, or the capacity of the man-made environment, plus the managed capacity for expansion (Rogers et al., 2008). Thus, it is not always beneficial for economies to develop at a fast pace. Similarly, many construction companies put too much attention on performance and ignore economic sustainability, which is reflected by their capacity to deal with such performance relating to organizational structure, partnering, accounting systems, among other things. A good performance in a single year does not guarantee long-term development in the following years. The indicators for evaluation should not only be centred on performance, but also the capacity of companies to deal with such performance.

Pearce (1988) describes sustainable development as being subject to a set of constraints which set resource harvest rates at levels not higher than the managed natural regeneration rate. In addition, he suggest using the environment as a waste sink on the basis that waste disposal rates should exceed the rates of managed or natural assimilative capacity of the ecosystem. The capacities which restrain economic development are described by Pearce et al. (1989, P.33), who stated that "sustainable economic growth means that real GNP per capita is increasing over time and the increase is not threatened by 'feedback' from either biophysical impacts (pollution, resource degradation) or from social impacts", including social and environmental considerations. In short, economies should be managed at levels that fall under such capacity in order to minimize both environmental and social fallout.

The World Bank (2002) defines sustainable development as: basing developmental and environmental policies on a comparison of costs and benefits and on careful economic analysis that will strengthen environmental protection and lead to rising and sustainable levels of welfare. In this definition, it is implied that economic factors should be carefully analyzed when evaluating social and environmental factors.

2.3.2 Economic sustainability and building materials

It is reported that the building structure accounts for approximately 20-25% of the total construction cost in a tall building (Elnimeiri and Gupta 2008). To address the goal of economic sustainability, the construction material production and construction industries must shift their use of resources and fuels from non-renewable to renewable forms, from waste production to reuse and recycling, from an emphasis on first costs to life cycle costs and full-cost accounting, where all costs such as waste, emission, and pollution are factored into the price of materials (Kibert et al., 2002).

The manner in which building materials are incorporated in the fabrication and structure of a building at the design stage and in which materials are handled and equipment deployed on the site or in a factory all affect the degree of expenditure of money and the overall economy of a building project (Stone, 1980, 1983).

2.3.3 Evaluation Methodology of economic sustainability – LCC

In building investment, in a similar fashion as many firms from other industries, traditional cost-accounting methods are widely used as the core indicators for investment decisions as well as alternative decision-making. However, such traditional cost-accounting systems lead to incorrect investment decisions concerning environmental costs (Cohan & Gess, 1994; Hamner & Stinson, 1995). For example, one problem is that maintenance costs and demolition costs appear outside the boundary of the traditional accounting system. A popular way of solving this problem has been to suggest the use of Life Cycle Cost (LCC) (Aye, et.al, 2000; Smith and Jaggar, 2007).

2.3.3.1 History of LCC

The development of LCC and similarly structured tools and methods has its origin in *the normative neoclassical economic theory* which states that firms seek to maximize profits by always operating with full knowledge (Cyert & March, 1963). This implies that the behaviour of the 'economic man' in neoclassical economic theory is always rational.

The term LCC was first used by the US Department of Defence in the mid-1960s (Epstein, 1996). In the mid-1980s, attempts were made to adapt LCC to building investments. Recently, several research projects have been carried out with the aim of developing the LCC methodology for the construction industry, and placing LCC in an environmental context.

2.3.3.2 Definition of LCC

In order to understand LCC fully, the following definitions of LCC are listed:

> LCC is the cost of an asset, or its parts throughout its life cycle, while fulfilling the performance requirements (BSI, 2008).
>
> LCC is an economic assessment of an item, area, system, or facility that considers all the significant costs of ownership over its economic life, expressed in terms of equivalent dollars. LCC is a technique that satisfies the requirements of owners for adequate analyses of total cost (kirk & Dell'Isola, 1995).
>
> LCC is a mathematical method used to inform or support a decision and is usually employed when deliberating on selection options (Bull, 1993).
>
> Traditional LCC is a technique which enables comparative cost assessments to be made over a specified period, taking into account all relevant economic factors both in terms of initial costs and future operational costs (Glucha & Baumannb, 2004).

> LCC is the total cost of ownership of machinery and equipment, including its cost of acquisition, operation, maintenance, conversion, and/or decommission (NSWTreasury, 2004).

The British Standard Institute (BSI) definition for LCC is adopted in this study because it includes the contents of all the other definitions.

2.3.3.3 <u>Components of LCC</u>

According to BSI (2008), the cost categories of LCC are shown in figure 2.1, which will be adopted in this study to compare the LCC of RC building and steel building.

LCC
- **Construction costs**
  - Construction works costs
  - Other construction related costs
  - Client definable costs
- **Maintenance costs (annual)**
  - Major replace costs
  - Redecoration
  - Minor replacement repairs
  - Unscheduled repairs, replacement and maintenance
  - Grounds maintenance
- **Operation costs (annual)**
  - Cleaning costs
  - Utilities costs
  - Administration costs
  - Overhead costs
- **Occupancy costs**
- **End of life costs**
  - Disposal inspections
  - Demolish
  - Reinstatement to meet contractual requirements
- **Non construction costs**
  - Finance cost
  - Taxes

Figure 2.1 Components of LCC

(Source: BSI, 2008)

The components of construction costs (or capital costs) are developed by BSI (2008). This cost category is cited in a considerable amount of research, and is adapted to analyze the capital costs of RC frame and steel frame in this study. The cost breakdown is shown in Figure 2.2.

Capital costs

- **1. Substructure**
  - Foundation
  - Basement Excavation
  - Basement Retaining Wall
- **2. Superstructure**
  - Frame
  - Upper floor
  - Roof
  - Stairs
  - External and internal walls
  - Windows and doors
- **3. Finishes**
  - Floor finishes
  - Ceiling finishes
  - Wall finishes
- **4. Fittings and furnishings**
- **5. Services**
- **6. External works**
  - Site works
  - Drainage
  - External services
  - Minor building works
  - Demolition and work outside the site
- **7. Preliminaries**
- **8. Contingencies**
- **9. Contractor's design fee**

Figure 2.2 Breakdown of capital costs

(Source: BSI, 2008)

As this study focus on structural frames, the capital costs of structural frames were investigated. The rest categories shown in Figure 2.2 (such as costs of finishes, external works and etc.) were not studied by this study.

2.3.3.4 Limitations of LCC

Currently, the application of LCC in the construction industry is still hindered significantly by a lack of standardized methods and the excuse of a lack of sound data. A government report issued by the Building Research Establishment (Clift & Bourke, 1998) on life cycle costing identified several factors that presently act as barriers to applying the LCC:

- The lack of universal methods and standard formats for calculating whole life costs.
- The difficulty in integration of operation and maintenance strategies at the design phase.
- The requirement for an independently maintained database on performance and cost of building components.
- It is found that clients have a lack of interest and trust in the value of whole cost exercise.

The above limitations could be summarized as an overall uncertainty in the reliability of LCC analysis. Although it is partly eliminated by combining risk assessment (Boussabaine & Kirkham, 2004) when computing LCC, the limitations identified above heavily restrict construction firms from making decisions with life cycle concern due to the insufficient amount of statistical information on potential costs. Capital cost or preliminary budget is generally used by most firms as one core indicator of the economic performance of a project (Wong et al., 2003).

The limitations of LCC are mitigated by the following strategies:

- Using traditional accounting method formats for calculating whole life costs. In this study, the LCC are used to compute the cash outflow when analysing the NPV and IRR of RC and steel frames.
- Identify the maintenance cost differences between an RC frame and a steel frame.
- Data collected from investigations on Singapore contractors and designers to obtain local data.

- In addition to giving the NPV of whole life costs, the capital costs, annual maintenance costs, non-construction costs, and end of life costs are separately given in this study.

2.3.4 Indicators of building economic sustainability

The LCC methodology has been proven as a good solution to evaluate the real economic performance when considering environment issues. Therefore, LCC categories are adopted in this study to evaluate economic sustainability.

In the LCC categories shown in Figure 2.1, operation costs and occupancy costs are mainly affected by the materials and size of enveloping elements, usage of buildings, and property management. The effect on operational costs and occupancy costs by using RC frames or SS frames is small, and are therefore not evaluated in this study. The indicators of building economic sustainability associated with structural elements are:

- Capital costs
- Maintenance costs
- End of life costs
- Non-construction costs.

2.4 Environmental sustainability and Structural materials selection

2.4.1 Environmental Sustainability

It is widely acknowledged that environmental factors play a very important role in global survival due to high risks, large affected areas and lasting effects on human survival. Climate change (IPCC, 2007), ozone depletion (UNEP, 2003), mineral extraction (OECD, 2001) and waste have been addressed as major environmental consequences. In order to eliminate the global warming trend, in 1997, the Kyoto Protocol for reduction in Green House Gases (GHG) was adopted at the Third Conference of parties to the UNFCCC (Cop3) held in

Kyoto, and commenced in February 2005.

Construction products are composed of a variety of constituents, each with its own complex web of inputs, outputs, and impacts that lead to their existence (Calkins, 2009). The impacts, both to the environment and to human health, begin during the raw material extraction phase with the destruction of ecosystems and habitats to extract mostly non-renewable materials from the earth. They continue in processing, manufacturing, and fabricating phase, using energy and producing emissions, effluents, and waste. The impact of transporting materials between phases are often significant because many site construction materials are bulky and heavy (CIRIA, 1999). Compared with the average consumer product, the use phase of building materials is relatively long, yet maintenance activities can pose risks to the environment and to human health. After the useful life of the material, disposal will result in more repercussions, yet the recent increase in recycling and reuse of materials such as asphalt and concrete has substantially reduced disposal to landfills. Therefore, the building designer has a role to play in minimizing environmental impact through resource efficiency, longevity, flexibility, demountability and the selection of materials (CIRIA, 1999).

2.4.2 Assessment systems for environmental sustainable building and structural materials

An environmental building assessment method reflects the significance of the concept of sustainability in the context of building design and subsequent construction work on-site. The primary role of an environmental building assessment method is to provide a comprehensive assessment of the environmental characteristics of a building (Cole, 1999) using a common and verifiable set of criteria and targets for building owners and designers to achieve higher environmental standards. It also enhances environmental awareness of building practices and lays down the fundamental direction for the building industry to move towards environmental protection and achieving the goal of sustainability (Ding, 2008).

Building environmental assessment is, in and of itself, a defined realm of enquiry with more rigorous explorations into weighting protocols, performance indicators, and so on (Cole, 2004). Environmental assessment methods have done the following: given focus to green building practices; enabled building performances to be described comprehensively; assisted in redefining progress. Improving the environmental performance of buildings within current cost and time constraints requires a different approach to the design process (Cole, 2004).

Sustainable building rating systems come in a variety of shapes and sizes. They are local, regional, national and international. Three of the most popular and widely accepted international systems (BREEAM and LEED) were reviewed. In addition, the Singapore local system, Green Mark, was reviewed as well.

2.4.2.1 UK BREEAM

The Building Research Establishment Environment Assessment Method (BREEAM) was developed by the UK Building Research Establishment (BRE) over two decades ago as a widely used environment assessment method for buildings.

BREEAM addresses wide-ranging environmental and sustainability issues and enables developers and designers to prove the environmental credentials of their buildings to planners and clients. According to a statement by BRE (2011b), BREEAM provides clients, developers, designers and others with: 1) market recognition for buildings with low environmental impact; 2) assurance that the best environmental practice is incorporated into a building; 3) inspiration to find innovative solutions that minimize environmental impact ; 4) a benchmark that is higher than current regulations; 5) a tool to help reduce running costs, improve working and living environments; and 6) a standard that demonstrates progress towards corporate and organizational environmental objectives. The family of BREEAM includes BREEAM Courts, BREEAM Data Centres, BREEAM Education, BREEAM Healthcare, BREEAM Industrial, BREEAM Multi-residential, BREEAM Offices, BREEAM Retail, BREEAM Prisons, and BREEAM Other Buildings, which enable BREEAM to be applied in all types of buildings.

In BREEAM, credits are awarded in ten categories according to performance. The percentage of credits achieved in each category is then multiplied by the corresponding BREEAM section weighting. These credits are then added together to produce a single overall score on a scale of Pass, Good, Very Good, Excellent and Outstanding.

The latest version of BREEAM schemes for assessing buildings was updated in 2011 by adding in BREEAM New Construction UK 2011(BRE, 2011a). Table 2.1 outlines the weightings for each of the nine environmental sections included in the BREEAM New Construction Scheme. It can be seen that those items affected by structural materials are worth about 1/3 of the total points.

Table 2.1 Point allocations in BREEAM New Construction (2011)

Categories	Available points	Applied structural materials
Management	**12%**	**Yes**
Sustainable procurement	*8*	*Yes*
Responsible construction practices	*2*	*Yes*
Construction site impacts	*5*	*Yes*
Stakeholder participation	*4*	*Yes*
Service life planning and costing	*3*	*Yes*
Health and Wellbeing	**15%**	**No**
Energy	**19%**	**No**
Transport	**8%**	**No**
Water	**6%**	**No**
Materials	**12.5%**	**Yes**
Life Cycle Impacts	*2-6*	*Yes*
Hard landscaping and boundary protection	*1*	*Yes*
Responsible sourcing of materials	*3*	*Yes*
Insulation	*2*	*Yes*
Designing for robustness	*1*	*Yes*
Waste	**7.5%**	**Yes**
Construction waste management	*4*	*Yes*
Recycled aggregates	*1*	*Yes*
Operational waste	*1*	*No*
Speculative floor and ceiling finishes	*0-1*	*No*
Land Use and Ecology	**10%**	**No**
Pollution	**10%**	**Yes**
Innovation (additional)	**10%**	**Yes**

(Source: BRE, 2011)

2.4.2.2 US LEED

The Leadership in Energy and Environmental Design (LEED) Green Building Rating System™ was developed by the US Green Building Council (USGBC) and officially launched in the US in 1998. Rating system Version 2.0 was released in March 2000, with LEED Version 2.1 following in 2002, Version 2.2 following in 2005, and Version 3 following in 2009. The scheme was inspired by other schemes, including BREEAM. Unless a country-specific LEED system is in place, the LEED US Criteria is used for any country in the world. LEED provides building owners and operators with a concise framework for identifying and implementing practical and measurable green building design, construction, operations and maintenance solutions. It is a voluntary certification program that can be applied to any building type and any building lifecycle phase.

The LEED systems evaluate environmental performance from a whole-building perspective over a building's life cycle. They promote a whole-building approach to sustainability by recognizing performance in seven key areas shown in table 2.2.

The current version, LEED 2009, uses the U.S. Environmental Protection Agency's Tools for the Reduction and Assessment of Chemical and Other Environmental impact's (TRACI) categories (USEPA, 2009) as the basis for weighting each credit. It also takes into consideration the weightings developed by the National Institute of Standard and Technology (NIST); Together, the two approaches provide a solid foundation for determining the point value of each credit. All certified projects receive a LEED plaque and a certificate, with ratings such as Certified, Silver, Gold or Platinum.

According to the guidebook of LEED for new construction v2009 (USGBC, 2009a, 2009b), those items affected by the applied structural materials are identified in table 2.2. About 43 points out of the total possible score of 110 are associated with structural material selection.

Table 2.2 Point allocations in LEED for new construction v2009

Categories	Available points	Applied structural materials
Sustainable Sites	**26/110**	
Credit 3 Brownfield Redevelopment	*1*	*Yes*
Credit 5.1 Site development- protect or restore habitat	*2*	*Yes*
Credit 5.2 Site development- Maximize open space	*3*	*Yes*
Water Efficiency	**10/110**	No
Energy and Atmosphere	**35**	
Prerequisite 2 Minimum energy performance	*required*	*Yes*
Credit 1 Optimize energy performance	*1-19*	*Yes*
Material and Resources	**14/110**	
Prerequisite 1 Storage and collection of recyclables	*required*	*Yes*
Credit 1.1 Building reuse--maintain existing walls, floors and roof	*1-3*	*Yes*
Credit 2 Construction waste management	*1-2*	*Yes*
Credit 3 Material reuse	*1-2*	*Yes*
Credit 4 Recycle content	*1-2*	*Yes*
Credit 5 Regional material	*1-2*	*Yes*
Credit 6 Rapidly renewable material	*1*	*Yes*
Credit 7 Certified wood	*1*	*Yes*
Indoor Air Quality	**15/110**	
Credit 3.1 Construction IAQ mgmt plan--during construction	*1*	*Yes*
Credit 4.3 Low emitting materials--floor systems	*1*	*Yes*
Credit 4.4 Low emitting materials--composite wood and agrifiber products	*1*	*Yes*
Credit 8.1 Daylight and views--daylight	*1*	*Yes*
Credit 8.1 Daylight and views--views	*1*	*Yes*
Innovation in Design	**6/110**	No
Regional Priority	**4/110**	No
Sustainable Sites	**26/110**	
Credit 3 Brownfield Redevelopment	*1*	*Yes*
Credit 5.1 site development- protect or restore habitat	*2*	*Yes*
Credit 5.2 site development- Maximize open space	*3*	*Yes*
Water Efficiency	**10/110**	No
Energy and Atmosphere	**35**	
Prerequisite 2 minimum energy performance	*required*	*Yes*
Credit 1 optimize energy performance	*1-19*	*Yes*
Material and Resources	**14/110**	

Categories	Available points	Applied structural materials
Prerequisite 1 storage and collection of recyclables	*required*	*Yes*
Credit 1.1 building reuse--maintain existing walls, floors and roof	*1-3*	*Yes*
Credit 2 construction waste management	*1-2*	*Yes*
Credit 3 material reuse	*1-2*	*Yes*
Credit 4 recycle content	*1-2*	*Yes*
Credit 5 regional material	*1-2*	*Yes*
Credit 6 rapidly renewable material	*1*	*Yes*
Credit 7 certified wood	*1*	*Yes*
Indoor Air Quality	**15/110**	
Credit 3.1 construction IAQ mgmt plan--during construction	*1*	*Yes*
Credit 4.3 Low emitting materials--floor systems	*1*	*Yes*
Credit 4.4 Low emitting materials--composite wood and agrifiber products	*1*	*Yes*
Credit 8.1 daylight and views--daylight	*1*	*Yes*
Credit 8.1 daylight and views--views	*1*	*Yes*
Innovation in Design	**6/110**	No
Regional Priority	**4/110**	No

(Source: USGBC, 2009)

2.4.2.3 Singapore GM

The Singapore Green Mark (GM) scheme was launched in January 2005 as an initiative to drive Singapore's construction industry towards more environmentally-friendly buildings (BCA, 2013). It was aimed at promoting sustainability in the built environment and to raise environmental awareness among developers, designers and builders when they start project conceptualization and design, as well as during construction.

BCA GM is a benchmarking scheme that incorporates internationally recognized best practices in environmental design and performance. It rates buildings according to five key criteria -- energy efficiency, water efficiency, environmental protection, indoor environmental quality, and other green and innovative features (BCA, 2012c). Based on an overall assessment, a building may be awarded one of four GM ratings: the GM certified, Gold, Gold^{plus} or Platinum award.

Based on the current version of BCA GM for new non-residential buildings (Version NRB 4.1) (BCA, 2012a), those items affected by structural materials are identified in table 2.3. About 42 points out of the total possible score of 190 are associated with structural material selection.

Table 2.3 Point allocations in BCA GM for new non-residential buildings (VNRB 4.1)

Categories	Available points	Applied structural materials
Part 1 - Energy Efficiency	**116 /190**	
1-1 Building Envelope - ETTV	*12*	*Yes*
1-2 Air-Conditioning System	*30*	*No*
1-3 Building Envelope – Design/Thermal Parameters	*35*	*No*
1-4 Natural Ventilation / Mechanical Ventilation	*20*	*No*
1-5 Daylighting	*6*	*Yes*
1-6 Artificial Lighting	*12*	*No*
1-7 Ventilation in Carparks	*4*	*No*
1-8 Ventilation in Common Areas	*5*	*No*
1-9 Lifts and Escalators	*2*	*No*
1-10 Energy Efficient Practices and Features	*12*	*No*
1-11 Renewable Energy	*20*	*No*
Part 2 - Water Efficiency	**17/190**	
2-1 Water Efficient Fittings	*10*	*No*
2-2 Water Usage and Leak Detection	*2*	*No*
2-3 Irrigation System	*3*	*No*
2-4 Water Consumption of Cooling Tower	*2*	*No*
Part 3 – Environmental Protection	**42/190**	
3-1 Sustainable Construction	*10*	*Yes*
3-2 Sustainable Products	*8*	*Yes*
3-3 Greenery Provision	*8*	*No*
3-4 Environmental Management Practice	*7*	*No*
3-5 Green Transport	*4*	*No*
3-6 Refrigerants	*2*	*No*
3-7 Stormwater Management	*3*	*No*
Part 4 - Indoor Environmental Quality	**8/190**	
4-1 Thermal Comfort	*1*	*No*
4-2 Noise Level	*1*	*No*
4-3 Indoor Air Pollutants	*2*	*No*

Categories	Available points	Applied structural materials
4-4 Indoor Air Quality (IAQ) Management	*2*	*No*
4-5 High Frequency Ballasts	*2*	*No*
Part 5 – Other Green Features	**7/190**	
5-1 Green Features and Innovations	*7*	*Yes*

(Source: BCA, 2013)

2.4.3 Limitations of BREEAM, LEED and GM

Although BREEAM, LEED, and GM are widely used, there are some limitations that result in frequent updates of those systems.

- Financial aspects have not been included in the evaluation framework of those systems (Ding, 2008).

- Currently none of the existing simplified building environmental assessment methods are comprehensively or consistently LCA-based, nor do they necessarily need to be given a primary role in market transformation. While some performance criteria in these methods are increasingly based on conventional LCA data, their strength lies in bringing a broader range of considerations to the assessment process while being respectful of simplicity and practicality to make them more widely accessible (Cole, 2004).

- Those systems cannot be used by a specific engineer such as a structural engineer for two reasons. One reason is that those systems require the input of complete information about a project while a structural engineer may not have sufficient information about the whole project. The second reason is that the assessment processes are too complicated. This requires a special expert to do the assessment such as a LEED AP for the LEED system or a Green Mark Manager (GMM) for the GM system.

- Most environmental assessment methods were developed for local use and do not allow for national or regional variations (Kohler, 1999).

In this study, the environmental sustainability indicators related to structural material addressed by BREEAM, LEED and GM are employed as reference for developing the conceptual framework. The respondents were not required to address such tools. In addition, the limitations of these systems can be overcome by integrating economic assessment methods and constructability assessment methods.

2.4.4 Evaluation methodology for environmental sustainability – LCA

2.4.4.1 Definition and principles

Life-Cycle Assessment (LCA) is a procedure to assess the sustainability of a product through consideration of all the environmental implications of development, from primary inputs to disposal of final output and by products, including wastes (ISO, 2006). In that respect, LCA has become a widely accepted method for evaluating the environmental impact in not only industrial sectors (Nakayama & Yaguchi, 2002), but also in the construction sector (Aguado et al., 2004; Harris, 1999; Lucuik et al., 2007; Petersen & Solberg, 2002).

Two possible different approaches to LCA have developed in recent years. One is to assign elementary flows and potential environmental consequences to a specific product system, typically as an account of the history of the product, which was used in this study. The other one is to study the environmental consequences of possible changes between alternative product systems.

A Life Cycle Assessment is carried out in four distinct phases, according to the ISO 14040 (2006) and ISO 14044 (2006) standards (refer to Figure 2.3).

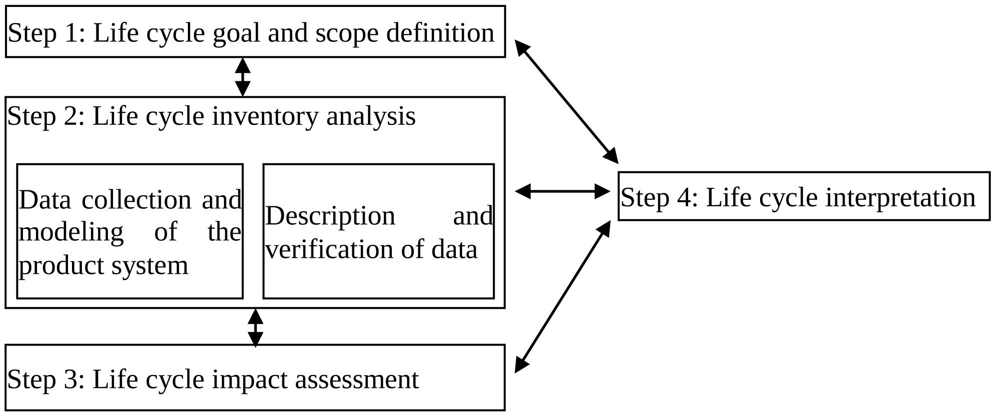


Figure 2.3 Stages of LCA

(Source: ISO 14044, 2006)

Where the goal and scope phase presented problems associated with setting study parameters, the inventory phase presented problems associated with finding and setting modelling parameters.

Inventory involves data collection and modelling of the product system, as well as description and verification of data. This encompasses all data related to environmental and technical quantities for all relevant unit processes within the study boundaries that compose the product system.

A reliable LCA requires the use of reliable Life-Cycle Inventories (LCI). Three problems occur when using LCI: 1) the allocation problem is one of the most controversial issues of LCA (Rebitzer et al., 2004) and one of the classical methodological problems in LCA (Russel et al., 2005); 2) Inappropriately severe cut-off criteria unnecessarily increase data costs while insufficient criteria leads to the exclusion of consequential flows (Reap et al., 2008); and 3) Local technical uniqueness becomes problematic when average or genetic data or models are used to represent processes that significantly differ from the norm (Reap et al., 2008).

Local data is an important point because in Singapore, reliable LCI data is scarce. In order to apply non-local LCI data in the form most suitable for the Singapore situation, Ossés de Eicker et al. (2009) states that an applicable LCI database should have the following characteristics: 1) all processes must be addressed individually; 2) all datasets should be clearly documented; and 3) different alternatives for the same product should be provided, related to technological variations.

2.4.4.2 Application

Several studies have been done to evaluate the environmental soundness of buildings and housing by conducting LCA.

Cole and Kernan (1996) evaluated the life cycle energy of a 50,000 ft^2 (4620m^2) three-story generic office building for alternative wood, steel and concrete structural systems in Canada. Blanchard and Reppe (1998) studied the total life cycle energy of a standard house in Michigan. They used typical LCA methodology to evaluate the embodied energy of the house. On the other hand, Harmaajaärvi (2000), used the EcoBalance model to study the ecological impacts of eco-villages and he indicated that eco-villages may not be very sound from an ecological point of view. Gerilla et al. (2005) evaluated the embodied emissions of different types of housing construction and materials used. They found out that certain materials in housing construction contribute to an increase in embodied CO_2 emissions.

In this study, the LCA-based tools such as BREEAM, LEED and BCA GM are used to develop those criteria under the factor 'environmental sustainability' in the conceptual framework. To obtain LCA data, for example, to investigate the CO_2 emission during construction stage, the information that respondents needed to provide were the amount of electricity consumption, diesel consumption, and gasoline consumption.

2.4.4.3 Limitations

The limitations of LCA (Durairaj, 2002) are stated below:

a) The nature of choices and assumptions made in LCA may be subjective.

b) Models used for inventory analysis or environmental impact assessments are limited by their assumptions, and may not be available for all potential consequences or applications.

c) Results of LCA studies focused on global and regional issues may not be appropriate for local applications.

d) The accuracy of LCA studies may be limited by the accessibility or availability of relevant data and data quality.

e) Uncertainty in effects of consequences.

2.4.5 Indicators of environmental sustainability

Since it is difficult to directly measure environmental impact, many assessment tools are developed based on the evaluation of strategies and a series corresponding performances.

2.4.5.1 Indicators addressed by BREEAM, LEED and BCA GM

BREEAM, LEED and GM have provided comprehensive environmental portfolios to evaluate environmental impact, yet these systems keep updating frequently because of the need to adjust parameters and ever-increasing data sources. Based on the criteria of these systems (see Table 2.1 to 2.3), it is possible to derive the following indicators used to assess the environmental performance associated with structural materials:

a) Percentage of reuse materials (reuse rate)

b) Percentage of recycle materials (recycling rate)

c) Waste

d) CO_2 emission

e) Water consumption

f) Noise

g) Air pollution.

In those systems, most of the points associated with structural material selection are earned by using recycled concrete and using products that have achieved typical certification.

2.4.5.2 Indicators addressed by other individual studies

Mourão (2007) states that the following parameters should be addressed when evaluating the environmental impact of a certain material.

a) The direct impact of its extraction -- the nature of the resources requested for its production;

b) The CO_2 emission produced, which is also addressed by González and García Navarro (2006) ;

c) Distances and forms of transport used to in distribution;

d) Risks for health/safety , which is also addressed by Burgan and Sansom (2006);

e) Possibility of its direct reuse, also addressed by Erlandsson and Levin (2005);

f) The recycling potential, which is also addressed by Maher and Kramer (2007);

g) The contribution of the material towards the environmental performance of the building during its use (environmental performance potential).

Embodied energy is also addressed by many researchers (Asif et al., 2007; Chen et al., 2001; Petersen & Solberg, 2002; Thormark, 2006). Embodied energy is defined as the quantity of energy required by all the activities associated with a production process, including the relative proportions consumed in all activities upstream, to the acquisition of natural resources and the share of energy used in making equipment and in other supporting functions i.e. direct energy plus indirect energy (Treloar, 1994). Embodied energy is an accounting methodology which aims to find the sum total of the energy necessary for an entire product lifecycle. This lifecycle includes raw material extraction, transport, manufacture, assembly, installation, disassembly, deconstruction and/or decomposition.

Life cycle energy consumption is pointed out as one parameter to assess environmental impact (Börjesson & Gustavsson, 2000; Guggemos & Horvath, 2005; Petersen & Solberg, 2002).

Construction waste is employed to evaluate environmental impact as well (Burgan & Sansom, 2006; Craighill et al., 1997).

Based on those indicators addressed by BREEAM, LEED, GM, and individual studies, the indicators of environmental sustainability affected by structural materials are classified into four categories in this study. They are:

- Material consumption. This category includes recycling rate, reuse rate, the potential of being recycled, the potential for being reused, and the material waste rate.

- CO_2 emission.

- Noise pollution during construction.

- Water consumption during construction.

2.5 Constructability and Structural materials selection

2.5.1 Definition and principles of Constructability

The term "constructability" in US and the equivalent concept "buildability" in the UK emerged in the late 1970s. This concept is employed and defined by many organizations.

- The Construction Industry Research Information Association (CIRIA) definition

  Constructability is the extent to which the design of the building facilitates ease of construction, subject to the overall requirements for the completed building (CIRIA, 1983).

- The Construction Industry Institute (CII) definition

  Constructability is the effective and timely integration of construction knowledge into the conceptual planning, design, construction, and field operations of a project to achieve the overall project objectives in the best possible time and accuracy at the most cost-effective levels (CII, 1993).

- CIIA definition

  Constructability is a system for achieving optimum integration of construction knowledge in the building process and balancing the various project and environmental constraints to achieve maximization of project goals and building performance (CIIA, 1993).

- Singapore BCA definition on Buildability

  Buildability is the extent to which the design of a building facilitates ease of construction as well as the extent to which the adoption of construction techniques and processes affects the productivity level of building works (BCA, 2011a).

Although the definition of buildability given by BCA is similar to the definition of constructability given by CIRIA (1983), the implications of buildability and constructability are different. In Singapore, the BDAS focuses on the use of buildable designs during the upstream design process to bring about greater productivity improvements, while CAS is used to tackle improvements in downstream construction methods. Designers' attention to buildable designs has to be complemented with builders' adoption of labor-efficient construction technologies to bring about greater ease in construction. It means that BDAS and CAS mainly emphasize labor-efficiency both upstream and downstream. Therefore, neither the buildability concept nor the constructability concept adopted by Singapore BCA is appropriate for this study because the implications are too narrow.

Among all these definitions, the CIIA definition was adopted to explain the concept of constructability as it takes environmental constraints into account.

The principles of constructability are given by O'Connor et al. (1986) and Trigunarsyah (2007):

- Design and procurement schedules are construction driven;
- Designs are simplified to enable efficient construction;
- Design elements are standardized;
- Owner, designer and constructor personnel review specifications in detail;
- Pre-assembly work is scoped in advance and module/pre-assembly designs are prepared to facilitate fabrication, transport and installation;
- Designs promote accessibility of manpower, material and equipment;
- Designs facilitate construction under adverse weather conditions.

Singapore BCA states Standardization, Simplicity and Single integrated elements (3S) are the principles of buildability, which is mainly measured by labor saving. However, other than labor saving, there are several aspects are implied in constructability concept, such as resource accessibility (O'Connor et al., 1986; Trigunarsyah, 2007), construction quality and safety (Ugwu et al., 2004).

2.5.2 Evaluation of constructability performance

2.5.2.1 <u>Evaluation by Singapore BDAS and CAS</u>

Singapore has pioneered the quantification of buildability based on two schemes known as the Buildable Design Appraisal System (BDAS) (BCA, 2004) and Constructability Appraisal System (CAS) (BCA, 2011a). It has culminated in statutory requirements for building designs to fulfil a Minimum Buildability Score and a Minimum constructability score. Under the Building Control Act, the requirement is a prerequisite for approval of submitted building plans.

The 3 key design principles on which a design is judged for buildability include Standardisation, Simplicity and Single integrated elements.

- Standardisation refers to the repetition of grids, sizes of components and connection details. A repeated layout, for example, will facilitate faster construction regardless of whether formwork or pre-cast components are used. Similarly, columns or external claddings of repeated sizes will reduce the number of mould changes whether on-site or in the factory.

- Simplicity means uncomplicated building construction systems and installation details. A flat plate system, for example, eases formwork construction as well as reinforcement work considerably. Use of pre-cast components reduces many trade operations on site and should improve site productivity, provided the standardisation principles are observed.

- Single integrated elements are those that combine related components together into a single element that may be prefabricated in the factory and installed on site. Pre-cast concrete external walls, curtain walls or prefabricated toilets are good examples of this.

In BDAS and CAS, the Buildability scores and Constructability scores are given according to the relative extent of labor saving that can be achieved by the use of different construction systems. Projects with higher scores are generally more buildable and fewer site workers are needed by the same contractor.

2.5.2.2 <u>Evaluation by other studies</u>

By reviewing the constructability assessment works of CII, Ugwu et al. (2004) concluded that an enhanced constructability process includes:

- Reduction in costs;

- Enhancement in the quality of the constructed facility;
- Improvements and shortening of the project schedule through encouraging innovative construction techniques;
- Improvements in safety during construction;
- Reduction in change and work orders;
- Reviewing projects during design to identify constructability issues as part of the value engineering process, which leads to significant savings in the project through improved productivity and reductions in claims, disputes and litigation?

2.5.3 Indicators of constructability performance

With reference to the indicators addressed in section 2.5.2, the 7 indicators of constructability performance can be summarized as follows:

- Construction costs saving;
- Labor saving;
- Construction schedule shorting (faster construction speed);
- Construction safety improvements;
- Element standardization, pre-assembly work and prefabrication;
- Accessibility of manpower, material and equipment;
- Ease of transportation and installation of elements.

2.6 Previous studies on selection of building materials

The material selection problem has been treated extensively in current literature through many approaches, such as multi-objective optimization (Ashby, 2000), ranking methods (Jee & Kang, 2000), index-based methods (Shanian & Savadogo, 2006), and other quantitative methods like cost–benefit analysis.

2.6.1 Models integrate environmental goals and budget requirements

Castro-Lacouture et al. (2008) developed a material selection model, named the mixed integer linear program (MILP), to improve green construction decision-making through the selection of materials. The model considers both design and budget constraints while maximizing the number of credits reached under LEED.

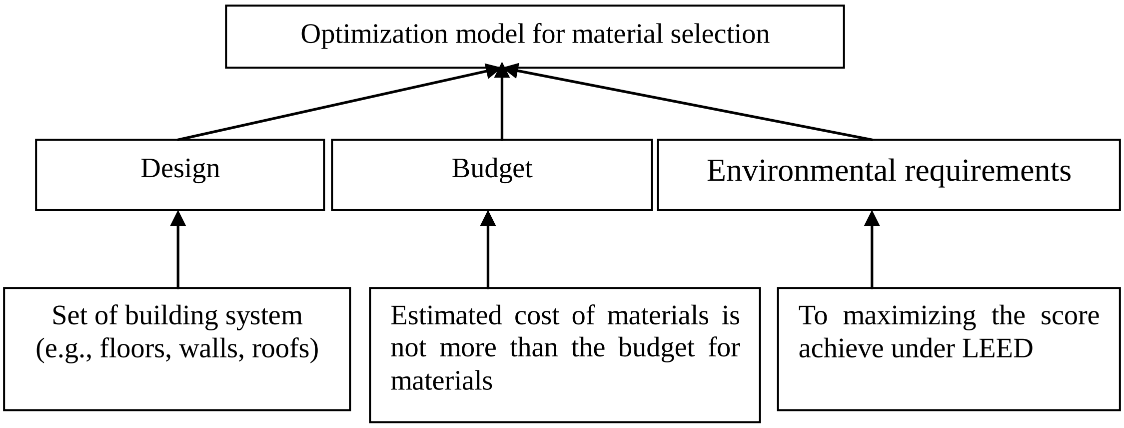


Figure 2.4 Material selection model

(Source: Castro-Lacouture et al., 2008)

The criteria and weight of the criteria in this program are based on LEED rating system. It cannot be directly used for structural material selection since constructability indicators are absent in this model.

Paya-Zaforteza et al. (2009) conducted a case study on 6 frames (four 2-bay frames, 3 bays 4 floors and 4 bays 4 floors) to test whether the embodied emissions and costs were related. The embodied emissions in their study involved emissions at the different stages of production and placement. A methodology to design RC building based on minimum embedded CO_2 emission and the economic cost is described as below:

2 objective functions:

$$CO_2 = \sum_{i=1,r} e_i \times m_i(x_1, x_2, \ldots, x_n). \qquad \text{(Eq. 2.1)}$$

$$C = \sum_{i=1,r} p_i \times m_i(x_1, x_2, \ldots, x_n). \qquad \text{.............................. (Eq. 2.2)}$$

Constraints: $g_j(x_1, x_2, \ldots x_n) \leq 0.$

Wherer, M_i is the measurement of materials;

e_i is CO_2 unit emission (Database BEDEC, 2007, in Spanish)

The authors concluded the following results: a) Embedded emissions and costs are closely related; b) The best solution for the environment are at most only 2.77% more expensive than the best cost solutions. c) The best cost solutions increase CO_2 emissions by 3.8%.

The limitations of this study are: a) the transportation emission data was not included in this study; b) only CO_2 emission is examined as an indicator of environmental impact; c) constructability indicators are absent in this model.

2.6.2 Models integrate environmental goals and constructability requirements

The traditional linear progression of a structural design (as shown in Figure 2.5) was summarized by Elnimeiri and Gupta (2008). In addition, they propose that sustainable parameters should be evolved as a circular progression model wherein each component is interrelated to the other.

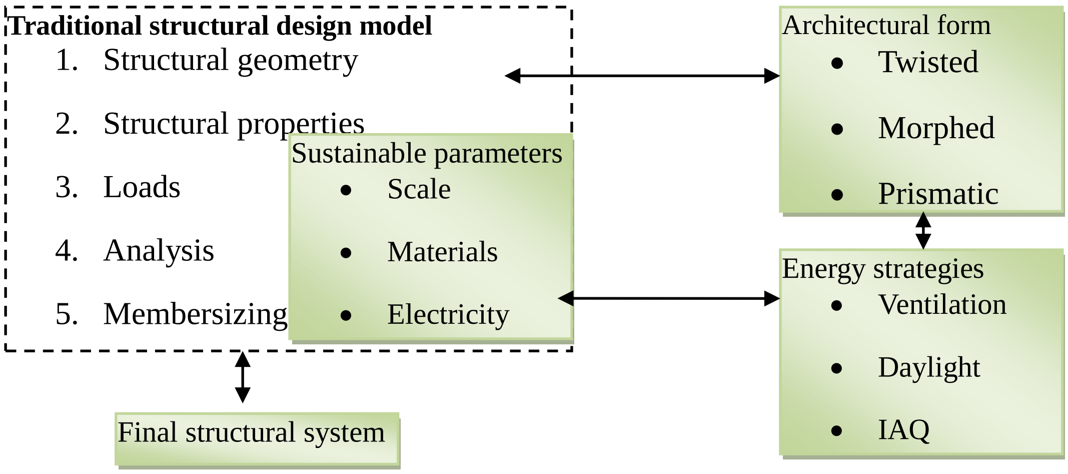


Figure 2.5 Sustainable approach for structural synthesis

(Source: Elnimeiri and Gupta, 2008)

Giudice et. al (2005) developed a systematic method which introduced environmental considerations in the selection of the materials used in components, meeting functional and performance requirements while minimizing the environmental impact associated with the product's entire life-cycle. The target of this model was to meet functional and performance requirements while minimizing environmental impact.

The limitation of these two models is that economic criteria are absent.

2.6.3 Model(s) integrate budget and constructability requirements

Sirisalee et al. (2004) used a multi-objective optimization method to develop a model specifically for structural material selection, which aimed to achieve 3 objectives: minimize thickness, minimize mass of casting and minimize cost. The result was that economic lightweight design is one of the best solutions (including material choice) that minimize both weight and cost.

The limitations of this study are that: a) the term "cost" used in this model is limited to the initial cost, which excludes the maintenance cost and deposit cost, and b) the environmental objective is absent.

2.6.4 Previous studies focus on methodology of decision on material selection

Ashby (2000) adopted the multi-objective optimization method to help decision-makers select material. It was found that trade-off surfaces give a method to visualize the alternative compromises, and that value functions (or 'utility' functions) identify the part of the surface on which optimal solutions lie. However, the application of this method was not described in Ashby's study.

Jee and Kang (2000) utilized the concept of entropy to evaluate the weight factor for each material property or performance index； TOPIS was used to rank the candidate materials. A model to select the optimal material for a flywheel was developed as well. However, a new assessment parameter system is necessary in order to apply the methodology now.

Granta (2009) introduced the Cambridge Engineer Selector (CES) methodology. This methodology involves two steps: the first step is screening and ranking and second step is to apply supporting information. The limitation of using CES is that the search for supporting information could be difficult, because it was not comprehensive and incomplete. Furthermore, this tool required a huge database for widely used material selection.

By producing a material selection decision matrix and a criteria sensitivity analysis, the Elimination and Choice Expressing the Reality (ELECTRE) model was used to obtain a more precise material selection for particular applications, including logical ranking of considered materials. Shanian and Savadogo (2006) suggested that the entropy idea is useful in the set of objective weights. However, no specific model was provided in their study.

2.6.5 Critique of existing models

The literature review shows that the building domain lacks a standard method that may help the decision-maker select more appropriate materials while taking into account the accomplishment of environmental goals and meeting design and budgetary requirements at the same time (Castro-Lacouture et al., 2009). Castro-Lacouture et al.(2008) and Paya-Zaforteza et al. (2009) developed their models for the selection of structural materials by integrating environmental and cost goals where constructability criteria were absent. Elnimeiri and Gupta (2008) and Giudice et al. (2005) developed their models for selection of structural materials by integrating environmental and constructability requirements and leaving out economic factors. Sirisalee et al. (2004) developed their model for the selection of structural materials by integrating the cost and constructability goal while environmental factors are excluded. Thus, there exists a gap in current models, which is that there is no model that integrates the economic, environmental and constructability requirements for structural frame material selection between RC and steel.

2.7 Summary

From the review of literature, this study defines sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs. Sustainable construction, as a subset of sustainable development, is important because the construction industry uses half of the total consumption of raw materials. As structural frame materials account for 20% - 25% of the total cost of a building and produce high environmental impacts, it is important to focus on these materials to achieve sustainable construction. In addition, it is important that the structural frame materials of a building have good constructability performance so as to optimize construction speed and manpower usage. Therefore, it is necessary to integrally evaluate the performance of sustainability and constructability when selecting structural frame materials.

The literature review showed that the most suitable method to evaluate the economic sustainability of structural frame materials is LCC. Based on the review of LCC cost categories, capital costs, maintenance costs, end of life costs, and non-construction costs are identified to be possible indicators for evaluating economic sustainability associated with structural frame materials of building projects.

From the literature review, the LCA method is found to be appropriate to evaluate the environmental sustainability of structural frame materials. The literature review uncovered the following criteria to evaluate environmental sustainability of structural frame materials: quantity of material consumed, CO_2 emission, noise pollution during construction, and water consumption during construction.

From the review of the concept and principles of constructability, cost saving, construction speed, labor saving, construction safety, construction quality may be used to evaluate constructability performance.

Four existing models on selection of building materials were reviewed. These considered one or two of these: environmental goals, budget requirements, constructability. The main limitation of these existing models is that they have are not comprehensive and did not integrate the three concepts of environmental sustainability, economic sustainability and constructability.

The limitations of the existing models suggest that a more comprehensive model is required, and provides a justification for this study.

CHAPTER 3 Life cycle of SS frame and RC frame

3.1 Introduction

This chapter reviews the literature on reinforced concrete (RC) and steel, and their usage in structural frames of buildings.

The advantages and disadvantages that RC and steel have are reviewed in Section 3.2. This is followed by a review on how concrete and steel are manufactured, transported and constructed as building frame.

Maintenance services that are needed by the two frames are next reviewed followed by how RC framed and steel framed buildings are demolished. Finally, the parameters used to compare performance of the two frames are reviewed.

3.2 Structural frames for buildings

3.2.1 RC frame

Reinforced concrete is one of the most widely used modern building materials. The principle theory of reinforced concrete is extremely simple: Put the reinforcing steel where there are tensile forces in a structural member, and let the concrete resist the compression (Allen & Iano, 2009). Concrete is “artificial stone” obtained by mixing cement and sand, which is then aggregated with water. Fresh concrete can be molded into almost any shape, which is an inherent advantage over other materials (Limbrunner & Aghayere, 2010). Concrete became very popular after the invention of Portland cement in the 19th century; however, its limited tension resistance prevented its wide use in building construction. To overcome this weakness, steel bars are embedded in concrete to form a composite material called reinforced concrete. Developments in modern reinforced concrete design and construction practice were pioneered by European engineers in the late 19th century. At the present time, reinforced concrete is extensively used in a wide variety of engineering applications (e.g., buildings, bridges, dams).

The extensive use of RC frames, especially in developing countries, is due to the following advantages (Fiona, 2009):

- Low production cost. In most countries, the aggregates (sand and water) are produced locally. Thus, the cost of concrete is low because of low raw material costs and transportation costs.

- Low labor costs. Skilled labor is not necessary because the production process and construction of RC frame are not complicated.

- Ease of production. Concrete production does not require expensive manufacturing mills. In some cases, single-family houses or simple low-rise residential buildings are constructed without any engineering assistance.

- Resistance to action of water. Concrete is used almost exclusively in water-retaining and underground structures such as bridges and piers, and so on.

- Compressive loading applications.

3.2.2 Steel frame

Steel was first manufactured in the United States in 1856 (Aghayere & Vigil, 2009). Its first use in a bridge was a railroad bridge across the Mississippi River in St. Louis, in 1874. The first skyscraper to have steel beams incorporated in its frame is generally recognised as the Home Insurance Building in Chicago, which was built in 1885 and demolished in 1929 (Geschwindner, 2008). The first all-steel skyscraper was the Rand-McNally Building in Chicago, which was built in 1888-1890. It began a continuous evolution in steel building structures that continues today as new ideas continue to spring up in the minds of architects and engineers who continue to build with steel.

Using steel as a structural material has following advantages (McCormac, 2008):

- High strength. The high strength of steel per unit of weight means that the weight of structures will be smaller.

- Uniformity. The properties of steel do not change appreciably with time, as do those of a reinforced-concrete structure.

- Elasticity. Steel behaves more closely to design assumptions than most other materials because it follows Hook's law up to fairly high stresses. The moments of inertia of a steel structure can be accurately calculated, while the values obtained for a RC structure are rather indefinite.

- Permanence. Steel frames that are properly maintained will last indefinitely.

- Ductility. In structural members under normal loads, high stress concentrations develop at various points. The ductile nature of normal structural steel enables it to yield locally at those points, thus preventing premature failure. The large deflection of a ductile structure will therefore give visible evidence of impending failure when overloaded or subjected to a sudden shake.

- Toughness. Steel members can be subjected to large deformations during fabrication and erection without fracture—thus allowing them to be bent, hammered, and sheared, and have holes punched in them without visible damage.

- Additions to existing structures. Steel structures are quite suited to having additions made to them, such as new bays or new wings.

- Miscellaneous. This includes: 1) an ability to be fastened together by several simple connection devices, including welds and bolts; 2) adaption to prefabrication; 3) speed of erection; 4) ability to be rolled into a wide variety of sizes and shapes; 5) possible reuse after a structure is disassembled; and 6) scrap value since steel is the ultimate recyclable material.

In spite having the above advantages, steel has following disadvantages (Salmon et al., 2009):

- Corrosion. The fatigue strength of steel members can be appreciably reduced when the members are used in aggressive chemical environments and subjected to cyclical loads.
- Fireproofing costs. The strength of steel structural members is tremendously reduced at temperatures commonly reached in fires when the other materials in a building burn. As a result, the steel frame of a building may have to be protected by materials with certain insulating characteristics.
- Susceptibility to buckling.
- Fatigue. Steel strength may be reduced if it is subjected to a large amount of stress reversal or even a large number of variations of tensile stress.
- Brittle fracture. Under fatigue-type loadings, low temperatures, or triaxial stress conditions, steel may lose its ductility, and brittle fractures may occur.

3.3 Structural frame design principles and frame elements

3.3.1 Design goals and principles

Referring to the mission of the American Institute of Steel Construction Committee on Specifications, which is to "develop the practice-oriented specification for structural steel buildings that provide for life safety, economical building systems, predictable behavior and response, and efficient use" (AISC, 2005), Geschwindner (2008) summarizes the basic goals of the design team in three words: ***safety, function***, and ***economy***.

To help achieve certain of safety, building codes and design specifications are published that outline the minimum criteria that any structure must meet. Building regulations are documents laying down the minimum requirements and standards that a building must comply with to ensure that the safety, hygiene and level of amenity are compatible with environmental and social requirements at the time of construction and throughout the lifetime of the building (BCA, 2012b). In Singapore, BCA plays an important role in building control. Although the economy may appear to be the primary concern of an owner, safety must be the primary concern of the engineers.

By reviewing the research on structural design (Aghayere & Vigil, 2009; Dorf, 1996; Geschwindner, 2008; Rosen & Heineman, 1996), it is possible to summarize the traditional structural design goals and principles in figure 3.1.

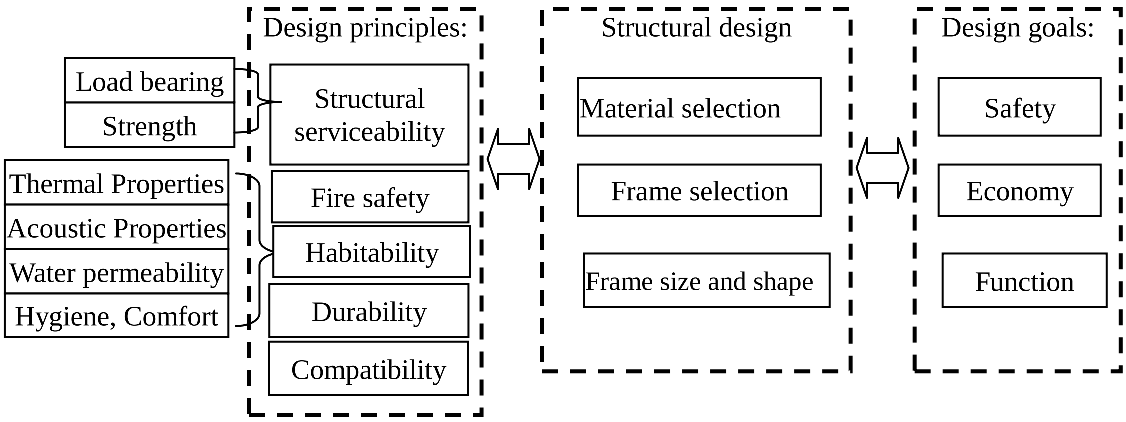


Figure 3.1 Traditional structural design goals and principles

3.3.2 *Elements of building frames*

A portal frame may be defined as a continuous or rigid frame that has the basic characteristic of a rigid or restrained joint between the support member or column and the spanning member or beam (Rees, 2009). The frame structural frame material is used to resist vertical and lateral wind or seismic loads that might occur in buildings. The following elements are defined in this study for the analysis of steel and RC frames (Underwood & Chiuini, 2007):

a) Beam element. A beam element is often subjected to uniaxial bending moment and minor axial force with negligible axial deformation.

b) Column element. A column element is often subjected to uniaxial or biaxial bending moment and significant axial force.

c) Brace element. A brace element is subjected to no more than axial force.

d) Shear beam element. It is a special beam element where shear deformation and shear yielding failure are dominant.

e) Joint-panel element. It is a special element to represent the shear deformation of the joint panel in the beam-column connection zone.

The materials used for these elements are investigated in this study.

3.4 Manufacturing of steel and RC

3.4.1 Reinforced Concrete (RC)

Concrete is produced from a mix of coarse and fine aggregates, cements, water, air, and often admixtures, additives and pigments. The selection of the ingredients is largely dependent on the design criteria and economic considerations.

3.4.1.1 Cement

The quality of the concrete is governed by the chemical composition of the cement, hydration and development of microstructure, admixtures, and aggregate characteristics. Portland cement concrete is the most widely used manufactured construction material in the world (Mamlouk & Zaniewski, 2006). Portland cement is an instant glue (just add water) that bonds aggregates together to make Portland cement concrete.

Portland cement is the main source of carbon emissions in the concrete production. The production of cement is an energy-intensity process using primarily fossil fuel sources. The most harmful properties of concrete are the high energy consumption and CO_2 release during the production of Portland cement (Calkins, 2009). Cement composes about 10% of a typical concrete mix in quantity but accounts for 92% of its energy demand. According to Vares and Häkkinen (1998), the carbon emissions of producing one tonne of a specific concrete product with a cement content of 280 kg/m^3 is 190kg, while the figure would increase to 240kg with the cement content rising up to 350 kg/m^3. In addition, due to the temperature needed during cement production, cement would account for over 60% of the energy used in concrete production.

In addition to CO_2 release and energy use, mining of limestone, the major raw material in cement, can cause habitat destruction, increased runoff, and pollutant releases to air and water. The key environmental aspects of cement production (Marlowe & Mansfield, 2002) are characterized by the World Business Council for Sustainable Development (WBCSD), as shown in table 3.1.

Table 3.1 Key environmental impacts during cement production

Categories	**Key environmental impacts**
Air Emissions	NO_x, SO_x, Dust/Particulates
Use of waste as fuel	Stakeholder concerns over release of dioxins, other chlorinated hydrocarbons, and heavy metals
Local nuisance	Noise, Vibration, dust, visual impact
GHG	CO_2
Land use and biodiversity	Primarily associated with quarrying activities

(Source: Marlowe and Mansfield, 2002)

3.4.1.2 Aggregates

In civil engineering the term aggregate means a mass of crushed stone, gravel, sand, and so on., predominantly composed of individual particles, but in some case including clays and silts (Mamlouk & Zaniewski, 2006). Coarse and fine aggregates in concrete make up between 60% and 75% of concrete volume. Aggregates are either mined or manufactured. Some are by-products of industrial processes or post-consumer waste products. Natural fine aggregates are quarried natural sand and coarse aggregates are either quarried or manufactured from crushed stone. Sand and gravel are typically dug or dredged from a pit, river, or lake bottom. They require minimal processing.

Crush rock, a manufactured aggregates, is produced by crushing and screening quarry rock or large-size gravel (Lippiatt, 2007).

Energy to produce coarse and fine aggregates from crushed rock is estimated by the PCA's Life Cycle Inventory to be 35,440 KJ/metric ton (Medgar et al., 2006). Energy sources are split evenly between diesel oil and electricity.

3.4.1.3 Ready mix concrete

According to U.S. National Ready Mixed Concrete Association (NRMCA, 2010), ready mix concrete is producing in following procedure:

Sand, aggregates, and cement are transported to the concrete plant by truck. Certain materials, such as inert aggregates, are stored outdoors in stockpiles. Moisture-sensitive materials, such as cement and fly ash, may be stored in high-capacity silos. As the materials are needed, they are transported by conveyor to large storage bins at the top of the block plant.

At the start of production, dry materials from the upper storage bins are discharged into the plant's stationary central mixer. The proportion of materials in the mix is custom-designed to meet the specifications for each project. Proportioning is controlled by computer to ensure quality control. The customer works with the ready-mixed concrete producer to determine characteristics such as aggregates size, slump, air content, and strength based on the intended use. Typical composition by volume is about 10-15% cement, 60-75% aggregates, and 15-20% water. Entrained air bubbles may account for 5-8%.

After mixing is complete, the mixture is discharged into a truck-mounted, rotating drum mixer. Rotating-drum truck mixers have a capacity of 9-11 cubic yards and discharge the concrete from the rear. Because slump loss can occur during transit, it is required that the concrete be discharged on the job site within 90 minutes or before 300 revolutions after the addition of water to the cement. Admixtures may be added to the concrete mix in situations of extreme temperature or long delivery times. Types of admixtures include air-entraining agents, water-reducing agents, and set-retarding agents. Vehicle maintenance is extremely important for ensuring safe and efficient transport of concrete products. Concrete plants typically include a full service garage to maintain their fleet of trucks.

3.4.1.4 Steel reinforcing

Adequate reinforcing in concrete will ensure its durability. Steel, either welded wire mesh or reinforcing bar, is the primary material used in RC to carry tensile force (Fiona, 2009).

A rebar, or reinforcing bar, is commonly used in reinforced concrete and reinforced masonry structures. It is formed from carbon steel, and is given ridges for better mechanical anchoring into the concrete (Limbrunner & Aghayere, 2010). Steel rebar manufacturing procedure is similar with other steel products, which will be introduced in section 3.2.2.

Rebar cages are fabricated either on or off the project site commonly with the help of hydraulic benders and shears (Underwood & Chiuini, 2007). However, for small or custom work, a tool known as a Hickey (a hand rebar bender), is sufficient. Rebar is placed by rodbusters or concrete reinforcing ironworkers with bar supports separating the rebar from the concrete forms to establish concrete cover and ensure that proper embedment is achieved. Rebar in the cages are connected by welding or tying wires.

3.4.2 Steel

The raw material required for the production of iron and steel can be grouped as follows:

- Ferrous materials (iron ores, scrap);
- Fuel and reducing agents (coke, coal, oil, gas);
- Fluxes (lime, alloying agents).

There are two main routes for the production of steel: production of primary steel using iron ore and scrap, and production of secondary steel using scrap only (Worrell et al., 1997). In the primary steel route, during the iron-making process, iron ore is reduced using coke and injected fuels to produce pig iron in a blast furnace (VDeh, 1992). The production of iron is the most energy-intensive step in the production of steel. Accordingly, the ratio of iron/ crude steel production is an indicator for structural change.

The Basic oxygen furnace (BOF) and open hearth furnace (OHF) are the processes that produce primary crude steel using pig iron and scrap as input. The OHF process, which is more common in developing countries, is rapidly replaced by BOF process because of OHFs lower productivity and higher capital cost. The share of steel production using the OHF process is an important indicator for energy efficiency. BOF process uses 25 to 35 percent recycled steel and produce automotive parts, appliances, packaging, and so on., for products characterized by the drawability of the material.

In secondary steelmaking, crude steel is produced in an electric arc furnace (EAF) using scrap. 95 percent of the raw material of scrap is recycled steel. Steel produced in EAF is used to produce structural beams, steel plates, reinforcement bars, and so on., for products characterized by the strength (Silva, 2005). Because pig iron production is not needed in this process, the EAF requires less energy. The share of secondary (EAF) steelmaking is used as an explanatory indicator of the changes in the production structure.

Steelmaking is followed by casting and shaping. Ingot casting is the classical process and is rapidly replaced by, more energy efficient, continuous casting process (Worrell et al., 1997). The degree of penetration of continuous casting process is also used as the main explanatory indicator of changes in energy efficiency. In the hot rolling process, profiles, sheets or wire are produced from the cast steel. After hot rolling, the sheets may be reduced in thickness by cold rolling. Additional energy is used and CO_2 emitted to produce cold rolled steel. The other explanatory indicator of the energy intensity of the product mix is the share of more energy intensive cold rolled products in the total product mix. Finishing is the final production step including annealing, pickling, and surface treatment.

The manufacturing processes are shown in figure 3.2.

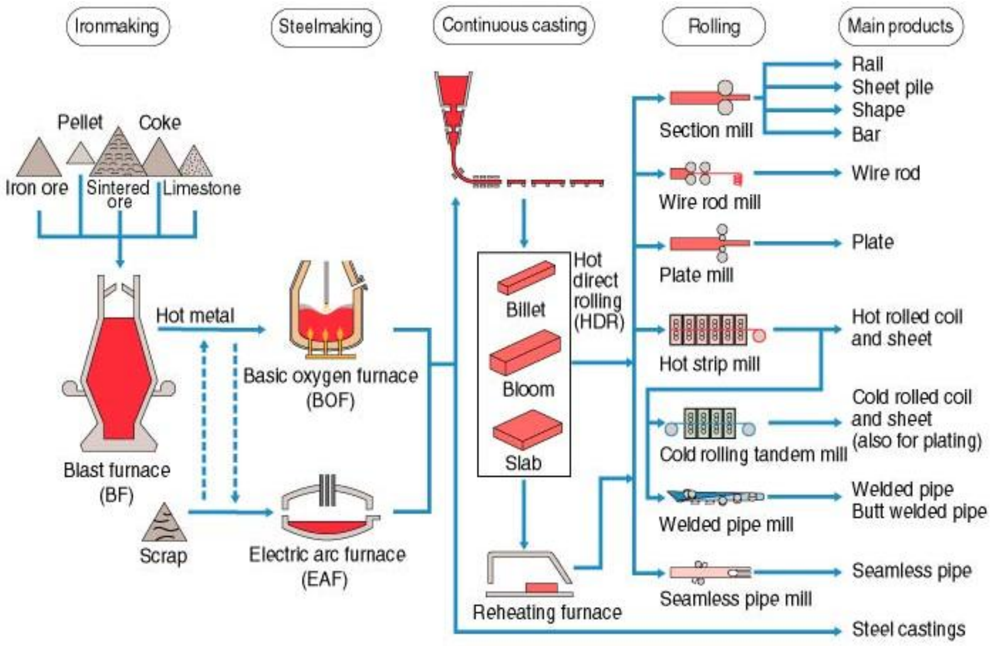


Figure 3.2 Steel manufacturing processes

(Source: Preston, 1991)

Environmental impacts evaluation of metals tends to focus on embodied energy (Pooliyadda & Dias, 2005). Important structural (process mix) indicators in iron and steel industry are feedstock (iron and scrap) and product type (iron and steel, slabs, hot rolled and cold rolled product, wire rods). The feedstock differences have a larger effect on energy use than differences in product mix. According to IISI (2002), 40% of steel production result from the BOF process. The energy intensity of BOF is about 26 GJ/ton of steel, while that of EAF is about 11.8 GJ/ton of steel.

However, toxic waste and emission releases to air (such as CO, SO_2, NOx, CO_2), and to a lesser degree to water and soil can be a greater concern based on the sheer volume of waste material created during the metal production process.

3.5 Transportation

There is few steel mill or cement factory in Singapore due to being a small country, thus, almost all structural frame materials are imported from the neighbouring countries. According to Singapore statistics (2007, 2008, 2009), 99.7% of cement used in Singapore in the recent 3 years is imported from Japan, Taiwan, Malaysia, Thailand and China; 96.6% of aggregates is imported from Indonesia, Malaysia, and China; and Steel is mainly imported from China (70.8%), South Korea (17.7%) and Japan (3.9%).

Cement, aggregates, and sand are delivered to concrete mix factory in Singapore to produce ready mixed concrete. Ready mixed concrete is then transported to construction site by drum trunk. The drum is turned at medium speed or about 8 rpm for 70 revolutions while driving to the job site (Chudley & Greeno, 2006).

Steel rebar and steel used for producing steel beam and/or column are delivered to prefabrication factories in Singapore to cut, weld or wrap into typical size and shape according to structural design. Once prefabricated, these steel products are transported to construction site by trunk.

On construction site, materials are moved from the storage point onto work plant for erection. Therefore, the main transportation of materials on construction site is vertical transportation by crane.

Once a building is demolished, demolish waste is produced. Part of waste is disposal in the way of land filling; part of demolished steel elements or concrete elements are delivered to construction site for reusing; and, part of demolished concrete is used for producing aggregates, and demolished steel is transported back to steel mills for producing steel.

The materials transportation routes are summarized in Figure 3.3.

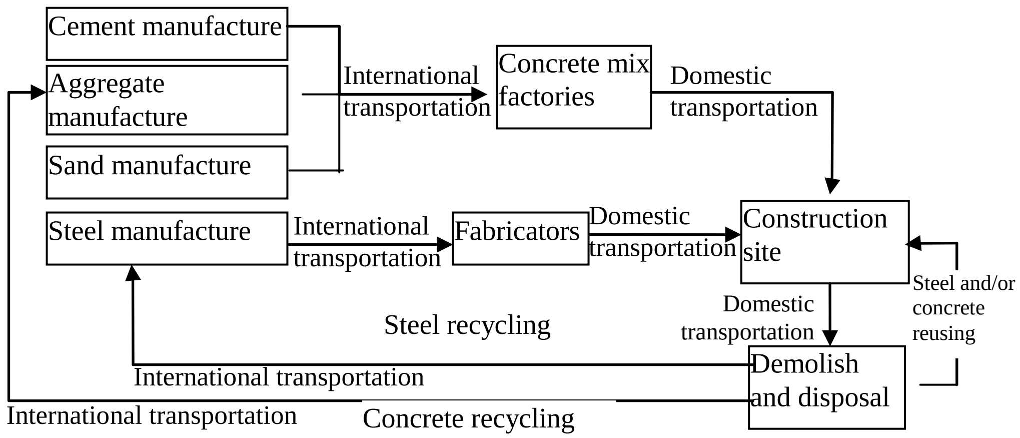


Figure 3.3 Materials transportation routes

Waterborne transportation is mainly adopted for international transportation of raw materials because of the geographical location of Singapore and low transportation cost. In addition, road transportation is mainly used for domestic material transporting.

3.6 Construction

Constructing a building follows complex procedures such as site preparation and planning, excavation, piling, constructing frame, building envelope elements, services, and interior fitting-out. Techniques adopted and resources consumption of a RC frame are different from those of a steel frame when doing works of site planning, excavation, piling, and constructing frame (refer to Section 3.5.1 to Section 3.5.3). Steel frame and RC frame require different plants due to extremely different construction techniques being used to erecting the frames. Those differences lead to varied costs including material costs, labor cost, machinery cost, and construction speed and so on.

3.6.1 Site planning

Site planning is a process that involves developing and implementing a specific organizational plan for an interior or exterior space. Site planning generally begins by assessing a potential site for development through site analysis. The main works of site planning related to structural frame include (Delves et al., 2002):

a) Managing materials and site compoud

Keeping the site well surfaced, well organised, clean and tidy helps minimise damage and soiling of materials. Site compounds for storage of steel frame and RC frame are different because the requirements of cement storage and rebar storage are extramly different from those of steel frame elements.

b) Maintain good horizontal and vertical site access

Horizontal site access consists of roads, conveyors, scaffolds and pumps. Vertial site access consists of cranes, hoists, lifts, pumps, ladders and stairs. As the weight of steel frame is lighter than RC frame, the load capability designed for transporting the materials of the two frames is different.

c) Managing facility for labor

As steel frame has more standarize works, this enable construction steel frame need less labor and shorter construction duration. Therefore, the facilities for labor are minimized.

d) Effective site lighting

To ensure works to continue during hours of inadequate natural light, effective site lighting system is required.

3.6.2 Frame construction

3.6.2.1 RC frame

There are five steps for casting a RC frame element (Figure 3.4): install reinforcement with prefabricated cages or mats, install formworks, pouring concrete, curing concrete and stripping forms (Chudley & Greeno, 2006). After concrete is cured and fastened, form works are removed for next floor constructing.

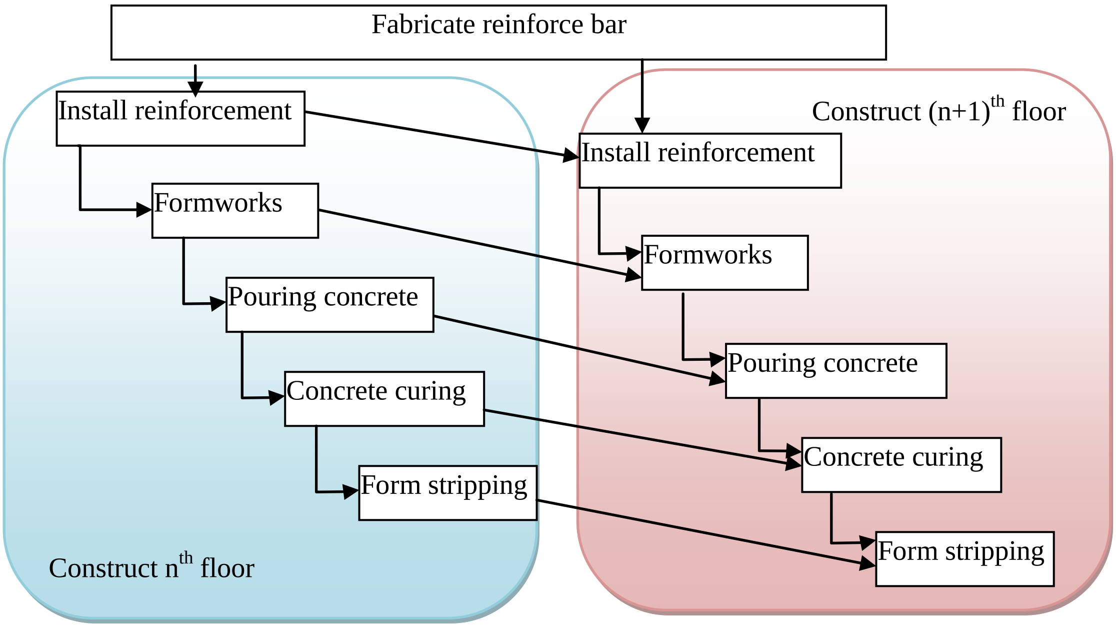


Figure 3.4 Processes of casting a RC frame element

The fabrication processes of rebars is composed by: a) Cutting reinforcing bars and reinforcing loops into designed length of rebar; b) Bending reinforcing loops; and c) Arranging reinforcing loops at designed distance and wired them with vertical bars (Chew, 2009). This forms prefabricated cages.

By analyzing the processes of constructing RC frame, it is found that the on-site works of RC frame construction are transporting, installing reinforcment cages, formworks, pouring and curing, form stripping. Comparing with steel frame, the on-site construction processed of RC frame are more complicated.

3.6.2.2 Steel frame

Different from RC frame construction process, most of works of structural steel works are normally prepared by specialist contractors, which is refered as off-site fabrication.

Each fabricating shop has its own characteristics for handling materials. The flow of the material from the stockyard at one end of the plant to the dispatch bay at the other end of the plant is generally through the material preparation bay, to the material assembly bay, and then to the painting bay (Vinnakota, 2006). The material is shipped from the mill to the fabricating shop in ordered dimensions, shapes, grades and quantities and is stored in the stockyard until required for fabrication. The pieces are then transferred through the shop by roller conveyors or, by overhead cranes through a series of saws, punches, and drills. The fabrication process of SS elements is shown in Figure 3.5.

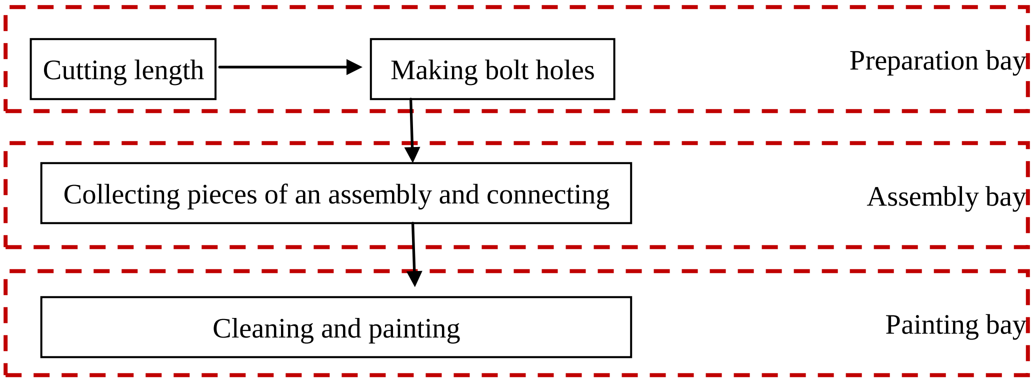


Figure 3.5 Fabrication of steel structural elements

(Source: Vinnakota, 2006)

After fabricated steel structural materials are delivered to construction site, steel frame is erected by following the processes: a) Set main columns over anchor bolts; b) Lift main rafters in line with columns; c) Attach wall girts; d) Attach roof purlins; e) Attach flange braces to girts and purlins; and f) Attach cable bracing (Vinnakota, 2006).

In selecting steel members for building, the designer should endeavor to use simple details and to use few different members and connections as possible in order to keep the labor cost down because fabrication and erection accounts for more than 60% of the cost of structural steel buildings, while materials cost accounts for only about 30% (Ricker, 2000).

Comparing the processes of constructing steel frame with the processes of constructing RC frame, it is found that the on-site works of steel frame construction are transporting, erecting, welding and bolting. Form works and curing process are not necessary for steel frame construction. This makes on-site steel frame construction works easier and faster. In addition, less work means less labor amount, therefore, the costs of labor and facilities provided to workers might be minimized when building a steel frame.

3.6.3 Plants

In modern construction industry, many types of plants are necessary from the beginning to the end of a construction project. Contractors may achieve higher construction efficiency by using proper plants. However, most of those plants are powered by diesel or electricity, which result in energy consumption and GHG emission. Although choice is usually based upon experience, familiarity with a machine, availability or personal preference, the most commonly used plants are described by Chudley and Greeno (2006) in table 3.2.

Table 3.2 Construction plants usage, types and power sources

Plants usages	**Plant types**	**Power sources**	**Applied for RC frame**	**Applied for steel frame**
Earth moving	Bulldozer and angledozer	diesel	Yes	Yes
Excavation	Scrapers	diesel	Yes	Yes
	Tractor shovel			
	Skimmer	diesel		
	Face shovel			
	Backacter			
Pile driving	Hammers		Yes	Yes
Horizontal transportation	Lorries and truck	diesel	Yes	Yes
Vertical transportation	Elevator and conveyor	Diesel or electricity	Yes	Yes
	Crane	Diesel or electricity		
Concrete mix	Concrete mixer		Yes	No

Plants usages	Plant types	Power sources	Applied for RC frame	Applied for steel frame
Concrete transportation	Concrete pumps	Diesel	Yes	No
Boring holes	Electric drill	Electricity	Yes	Yes
Cutting and chasing work.	Electric hammer	Electricity	Yes	Yes
Vibrators	Poker Vibrators	Electricity or petrol	Yes	No
	Vibration tampers			
	Clamp vibrators			
Moving liquids vertically or horizontally	Pumps	Electricity	Yes	No
Consolidating filling materials or to compact surface finishes	Rollers	Diesel or petrol	Yes	Yes

(Source: Chudley and Greeno, 2006)

Since the techniques for constructing RC frame and steel frame are different, the plants type and working hour are different. For example, vibrators, necessary plants when pouring concrete, might not be used for constructing steel frame. Therefore, the energy consumption by plants used for building the two frames are different.

3.7 Maintenance

3.7.1 Fire protection

Fire is a rapid, persistent chemical reaction that releases heat and light, especially the exothermic combination of a combustible substance with oxygen. A fire is categorized as both a natural hazard and a technological hazard that occurs in both the natural and built environments (Underwood & Chiuini, 2007). Fire not only kills and maims, destroys lives, it destroys personal property, the built fabric and whole communities.

Structure fire protection is generally known as a passive measure of fire protection, incorporated within the design specification of each element of construction (Sarkar & Saraswati, 2008).

3.7.1.1 Concrete - structure fire protection is generally not needed

Concrete does not burn: it cannot be 'set on fire' like other materials in a building and it does not emit any toxic fumes when affected by fire. It will also not produce smoke or drip molten particles (Rosen & Heineman, 1996). For these reasons, in the majority of applications, concrete can be described as virtually 'fireproof'. Concrete's inbuilt fire resistance maintains airtight construction that stops smoke from spreading, and the ability to maintain the building's strength during a fire. The continuing structural integrity is reduced in fire; furthermore, smoke damage reduces the magnitude of insurance claims (Underwood & Chiuini, 2007). It also lessens the use of raw materials as the structure can be reused, rather than being consumed in the fire or in need of demolition as the structure has melted and buckled.

According to Limbrunner and Aghayere (2010), a 100mm thick, single leaf masonry or concrete wall provides two hours fire resistance, which is up to four times greater than that typically required for housing. Similarly, precast concrete flooring will resist fire for at least one hour, which can easily be extended to two hours with a minor design modification. As a material, concrete meets the requirement for fire protection, in respect of surface spread of flame which is the highest product performance.

While concrete structures that comprise buildings are able to achieve fire-resistance ratings without additional fireproofing, concrete can be subject to severe spalling, particularly if it has elevated moisture content. Fireproofing is available for concrete but this is typically not used in buildings. Instead, it is used in traffic tunnels and locations where a hydrocarbon fire is likely to break out.

Fire protection for concrete structures is not needed as the material has inherent fire resistance of up to four hours. This removes the time, cost and separate trade required to attend the site for fire protection.

3.7.1.2 Structural steel frame - external insulation for fire protection is required

Structural steel requires external insulation (fireproofing) in order to prevent the steel from weakening in the event of a fire (Geschwindner, 2008). When heated, steel expands and softens, eventually losing its structural integrity. Given enough energy, it can also melt. Heat transferred to the steel can be slowed by the use of fireproofing materials.

Common fireproofing methods for structural steel include intumescent, endothermic and plaster coatings as well as drywall, calcium silicate cladding, and mineral or high temperature insulation wool in the form of blanket (Salmon et al., 2009). Steel and concrete compete against one another not only on the basis of the price per unit of mass but also on the basis of the pricing for the fireproofing that must be added in order to satisfy the passive fire protection requirements that are mandated through building codes.

3.7.2 Anti-corrosion protection

Corrosion is the disintegration of an engineered material into its constituent atoms due to chemical reactions with its surroundings. Steel used in exterior environments can be affected by corrosive conditions resulting from seawater contact, de-icing salts, and industrial or urban pollution. These potentially corrosive contaminants are made even stronger in hot humid location (Calkins, 2009), like in Singapore.

Corrosion phenomena on load bearing component are frequently associated with a considerable decrease in their load bearing capability.

Plating, painting, and the application of enamel are the most common anti-corrosion treatments. They work by providing a barrier of corrosion-resistant material between the damaging environment and the (often cheaper, tougher, and/or easier-to-process) structural material. Plating usually fails only in small sections, and if the plating is more noble than the substrate (for example, chromium on steel), a galvanic couple will cause any exposed area to corrode much more rapidly than an unplated surface would (Salmon et al., 2009). For this reason, it is often wise to plate with a more active metal such as zinc or cadmium.

For RC framed building, once the building is completed, reinforced rebar is hidden into concrete. In some extent, concrete is regarding as a protecting coat of reinforced rebar from corrosion. Thus, anti-corrosion treatment to a normal RC framed building is not necessary for maintenance.

For steel framed building, if the steel elements are explored to surrounding environment, anti-corrosion treatment is necessary for building maintenance. If there is a layer of concrete covering steel element, anti-corrosion treatment is not necessary anymore.

3.8 End of life – Demolition and recycling

3.8.1 Demolish

Demolition of a building or structure can be considered under two headings: a) Taking down or removals: partial demolition of a structure; b) Demolition: complete removal of a structure (McGrath & Anderson, 2007).

There are 6 types demolish methods:1) Hand demolition; 2) pusher arm demolition; 3) deliberate collapse demolition, 4) demolition ball techniques (should not be used on buildings over 30m high); 5) wired rope pulling demolition; and 6) demolition by explosives. Choice of demolition methods are determined by type of structure, type of construction, and location site (Kibert, 2008).

Concrete waste from construction and demolition is an environmental concern, but great strides have been made in the last decade to lessen the waste burden through reuse of concrete debris. Concrete is estimated to account for 67% by weight of construction and demolition waste – the largest single component (U.S.EPA, 1998).

3.8.2 Reuse

According to the waste hierarchy, the options for waste management in order of preference are: waste minimization; reuse; recycling, incineration with energy recovery, and composting; and lastly incineration without energy recovery, and landfill (BRE, 2007).

Reuse is high in the waste hierarchy, but structural items such as sections or I-beams may be difficult to reuse for two reasons (Conroy et al., 2007). One reason is that it is difficult to derive the strength characteristics such as shear and bending of a demolished frame element. This enable designers reuse demolish material if its strength properties is unknown or in doubt. The other reason is that most structural elements are designed with very long service lives and are not installed with reuse in mind. Once those elements are demolished, it is difficult to directly reuse them in new construction project.

3.8.3 Recycle

3.8.3.1 Recycled concrete

About 75-80% of secondary and recycled aggregates are thought to end up as sub-base and fill, including use in road building and airfield pavements (Conroy et al., 2007). However, the concrete industry actively utilizes industrial ecology in the production of modern concrete products due to concrete's inherent inert nature. The constituents of concrete can be recycled materials, and concrete itself can also be recycled. These materials are available for locally recycling. Concrete pieces from demolished structures can be reused to protect shorelines, for example in gabion walls or as rip rap.

Recycled concrete can be used as aggregates in new concrete, particularly the coarse portion. When using the recycled concrete as aggregates, the following should be taken into consideration (McGrath & Anderson, 2007):

a) Recycled concrete as aggregates will typically have higher absorption and lower specific gravity than natural aggregates and will produce concrete with slightly higher drying shrinkage and creep. These differences become greater with increasing amounts of recycled fine aggregates.

b) The chloride content of recycled aggregates is of concern if the material will be used in reinforced concrete. The alkali content and type of aggregates in the system is probably unknown, and therefore if mixed with unsuitable materials, a risk of alkali-silica reaction is possible.

c) Recycled aggregates from crushed concrete and masonry offer a range of high-grade and low-grade applications in construction. According to BS 8500: 2002, coarse aggregates in a wide range of concrete mixes can be replaced up to 20% by crushed concrete.

d) Recycled concrete can be less expensive than natural aggregates because concrete is easily recycled on-site by bring in equipment to break, remove, and crush the old material. This practice also can save on landfill and transportation fees.

3.8.3.2 Recycled steel

Steel, easily separated magnetically from other wastes, is one of the most recycled construction materials. Appliance recycling rates remained stable at 90 percent as did structural steel at 97.5 percent, while construction reinforcement steel (i.e. rebar) increased slightly to 70 percent (SRI, 2009). These steel recycling rates accomplish much more than simply saving landfill space. For every ton of steel recycled, 2500 pounds of iron ore, 1400 pounds of coal and 120 pounds of limestone are conserved.

Metal scrap that is collected for recycling is material that does not have to be managed as a waste. It is a valuable resource that is converted into value-added commodities. Perhaps even more importantly, recycled metal substitutes or displaces the necessity to mine new metal.

Consequently, metal recycling offsets primary production processes—and their associated environmental impacts s and energy consumption—required to dig, crush, grind and otherwise metallurgical process virgin ore. Recycling increases the material and energy efficiency of product systems throughout the life cycle and thus is good management practice.

Steel recycling has the following characters (SRI, 2006):

a) Recycling of metals has environmental, economic and social value. Consequently, and for many years, metals from end-of-life products are widely recycled at high rates.

b) Recycled metal is readily sold on the market. The constraint to greater levels of metal recycling is the availability of feedstock material.

c) Metals are characterized by metallic bonding that provides distinct structures and properties. As this type of bonding is not affected by melting, metals can be, and are, recycled over and over again.

d) Material grade is determined by conformity to established specifications. The origin of metal (whether primary or recycled) in a specific lot of material is driven by availability and economics.

e) Metal may be lost during product use (e.g., via corrosion or wear), and some material may not be economically recoverable at end-of-life due to material dispersion or difficulties in separating components.

3.8.3.3 The end-of-life recycling approach

The end-of-life recycling approach encourages manufacturers, policy-makers and other decision-makers to evaluate real performance and improve the design and management of products, including their disposal and recycling. This forward-looking perspective supports sustainable development. By supporting solutions where high amounts of metal are made available for the future by recycling, it assists society in meeting the needs of the present without compromising the ability of future generations to meet their own needs (WCED, 1987).

A designer using an end-of-life recycling approach focuses on optimizing product recovery and material recyclability (McGrath & Anderson, 2007). By facilitating greater end-of-life recycling, the decision-maker mitigates the loss of material after product use. This approach assesses the consequences at the end-of-life of the product based on established technical practices, and supports decisions for an efficient market. This concept allows design for recycling.

3.8.4 Landfill

A landfill is a site for the disposal of waste materials by burial and it is the oldest form of waste treatment. Historically, landfills have been the most common methods of organized waste disposal and remain so in many places around the world because of low disposal cost.

As landfill taxes increases to a value where recycling or incineration become viable alternative, or legislation, most of demolish waste will end up disposed of in the ground (Conroy et al., 2007). Furthermore, BRE (2007) recommends that landfill or combustion is the final option where no energy recovery systems are in place. Only a limited of construction and demolition waste can be incinerated but this is costly and has environmental implications, such as air pollution as well as GHG emission.

3.9 Parameters for comparison of differences between structural steel and RC frames

In order to address the variables described in chapter 4, which are the parameters indicating differences in economic performance, environmental performance, and constructability performance between steel frames and RC frames are further investigated in this section.

3.9.1 Parameters for comparison economic sustainability differences between structural steel frame and RC frame

There has been considerable research examining the economic sustainability of steel frames and RC frames. The parameters used to compare the difference in economic sustainability between the two frames and important findings are listed in Table 3.3.

Table 3.3 Previous studies on economic sustainability of steel and RC frame

Authors (Year)	**Parameters**	**Findings**
Sim (2007)	Capital cost	HDB using steel instead of concrete to construct lift shafts, which achieved an overall cost savings about 20%.
Liew (2007)	Material cost	Using steel could minimize material used, waste and disturbance, which contribute to minimize material cost.
Zhou (2005)	Additional income	Addition 5％—8％using area is obtained by using steel instead of concrete to construct, which may result addition income.
Andrews (2004)	Foundation costs	Foundation costs of RC frame are more expensive
Booth (1999)	Capital cost	When compared to standard construction, the metal building should be cheaper. The real cost advantage comes into play when the building area is greater than 10,000 ft. Steel building has more flexible building uses.
Achulitz, et al. (2000)	Maintenance cost	For steel building, modern anti-corrosion systems have a life expectancy of 15-20 years. Maintenance cost is necessary for renewing and repairing after the system has expired. This is not happened in RC building.

Foundation costs were excluded from the above parameters as this study only focuses on upper structural frames. Material costs are considered as a sub-category of capital costs in this study. Additional incomes earned by additional useable area (Zhou, 2005) and flexible uses of internal space (Booth, 1999) are adopted as parameters of economic sustainability.

With reference to the indicators of economic sustainability addressed in section 2.2.4, the parameters used to compare the differences in economic sustainability between RC frames and steel frames in this study are: capital structural costs, maintenance costs, non-financial costs, end of life costs, and additional incomes.

3.9.2 Parameters for comparison environmental sustainability differences between structural steel frame and RC frame

The Canadian Wood Council (1997) studied the Green House Gas (GHG), polluted air, solid waste, and ecological resource usage produced by steel, wood and RC buildings from a life cycle view. It reported that all of the four categories were produced in greater quantities by concrete buildings than steel buildings.

Eaton and Amato (1998) studied two office buildings with full air-conditioning, and reported that there was no significant difference between the environmental performance (in terms of embodied energy, embodied CO_2 and operating energy/CO2) of steel framed office buildings in comparison with concrete framed office buildings. They concluded that energy consumption and CO_2 emission could be used as relevant environmental parameters for life cycle assessments.

Jönsson et al. (1997) used the method of LCA to compare the environmental impact of the structure of concrete versus steel frames in buildings throughout their life cycle. In their study, 50 years was assumed to be a building's service life. Eight parameters that weighted heavily were the use of fossil fuels, CO_2, electricity, NOx, SOx, alloy materials and waste. By using three quantitative assessment methods -- the Environmental Priority Strategies in product design (EPS), the Environmental Theme Method (ETM) and the Ecological Scarcity Method (ESM) -- they concluded that the span between the highest and lowest values were not significant enough to draw any conclusions about what frame has the lowest environmental impact in spite of steel frames registering a slightly higher environmental impact than the other frames.

Lin (2003) investigated the CO_2 emission and solid waste produced by steel and RC buildings in Taiwan. He found that CO_2 emission and solid waste produced by RC structures was about 1.5 times that of a steel structure, from material production to the demolition stage. Furthermore, the solid waste produced by a RC structure is about 4 times that of a steel structure in demolition stage.

Peyroteo et al. (2007) compared the environmental impact of reinforced concrete versus steel structures. In their study, five parameters were selected in order to make the assessment. According to the values regarding the parameters caused by the manufacturing and transport of necessary materials, the energy consumption, water consumption, CO_2 emission and NOx emission of steel structures were presented as being greater than reinforced concrete structures. Although the SO_2 emission of reinforced concrete does more damage to the environment, the difference is only 0.8kg. Therefore, it was concluded that RC structures are friendlier to the environment. However, the fact that the steel is a resource that may reach a recyclable rate of 100% was not considered in their study. The environmental impact caused by demolition was not taken into account either.

Contrary to Peyroteo's results, Guggemos and Horvath (2005) from the US and Su et al. (2008) from China published their opposing results which found that energy consumption and other polluted air emissions produced by RC buildings are greater than those produced by steel buildings. Furthermore, Guggemos and Horvath (2005) pointed out that steel buildings have greater quantities of Volatile Organic Compound (VOC) and heavy metal (Cr, Ni, Mn) emissions.

Achulitz et at. (2000) studied the environmental impact from another perspective, using recyclability and disposition. They found that steel is 100% recyclable and constitutes approximately 50% of the raw material for the production of crude steel worldwide. The recycling of steel is very much simplified by its magnetic properties. This guarantees the fast sorting of building debris. Steel and iron products that are disposed of in landfill sites decompose to oxidized products without harming the environment.

The parameters used by these studies and comparative result are shown in Table 3.4.

Table 3.4 Research on environmental impacts by concrete and steel building

Authors/year --country	**Parameters**	**Concrete/Steel**
Canadian Wood Council (1997) --Canada	Green House Gas	1.24 times
	Polluted air	1.17 times
	Solid waste	1.44 times
	Ecological resources usage	1.7 times
Eaton and Amato (1998)	embodied energy, embodied CO2 and operating energy/CO2	no significant difference
Lin (2003) --Taiwan	CO_2 emission	1.5 times
	Waste	4 times
Guggemos and Horvath (2005) --US	Energy use, CO_2, CO, NO_2, particulate matter, SO_2, and hydrocarbon emissions	Concrete > Steel
	Volatile organic compound (VOC) and heavy metal (Cr, Ni, Mn) emissions	Concrete < Steel
Peyroteo et al. (2007) --Portugal	Energy consumption, Water consumption, CO_2 emission, NO_x emission	Concrete < Steel
	SO_2 emission	Concrete > Steel
Su et al. (2008) --China	Life-cycle energy consumption	Steel: 75.1%*Concrete
	Environmental emissions	Concrete > Steel

Authors/year --country	Parameters	Concrete/Steel
Liew (2007) --Singapore	Minimum waste	Steel is not wasteful material, and all waste can be recycled
	Health and aesthetic	Steel construction is a safety process
	Recycling	All steel can be recycled, and on 45% of current steel use is from a recycled source
	Reuse	Steel components can be dismantled and reused
Zhou (2005) --China	Solid waste	Steel < RC
	Water consumption during construction	Steel < RC because of the dry construction
Burgan and Sansom (2006)	Waste minimization	Steel is better than RC
Tam and Le (2008)	Waste	Steel frames may produce less waste because of long-life and prefabrication

The best way to deal with material waste is not to create it in the first place (Gavilan & Bernold, 1994). Tam and Le (2008) recommended the following measures to reduce waste in the design and construction stages: a) use long-life construction materials, such as steel; b) use environmentally-friendly construction methods, such as prefabrication; c) use recyclable materials; d) reuse materials; e) use secondary materials; and f) Avoid complex and labor-intensive operations.

With reference to the indicators addressed in section 2.4.5, as well as the parameters above, the following parameters have been identified to indicate the differences between the environmental sustainability of RC frames and steel frames.

- Material consumption. This category includes the material recycling rate, the material reuse rate, the potential for being recycled (material recyclability), the potential for being reused (material reusability), and the material waste rate.
- CO_2 emission.
- Water consumption during construction.
- Noise produced during construction

3.9.3 Parameters for comparison constructability performance differences between structural steel frame and RC frame

A considerable amount of research has compared the constructability performance of the two frames. The parameters used to compare the differences in the constructability of the two frames and the important findings are listed in table 3.5.

Table 3.5 Previous studies on constructability performance of steel and RC frame

Authors / Year	Parameters	Findings
Booth (1999)	Construction Speed	Constructing a metal building is faster than standard RC building.
Langdon et al. (2002)	Construction Speed	Efficient construction process could be achieved by member standardization and repetition.
Silva (2005)	Construction Speed Safety Flexibility and quality	Steel construction is clearly well equipped to deal with reduced execution; It is at the forefront of prefabrication, therefore eliminate many risks of on-site production. The inherent properties of the base material steel help provide much greater freedom in the conceptual phase, therefore helping to achieve greater flexibility and quality.
Burgan and Sansom (2006)	Construction Speed Safety	Steel building has good performance in these aspects during construction process.
Liew (2007)	Construction Speed Quality	Steel construction is installed rapidly on site. Project can be completed faster with earlier return of investment. Steel is a high quality, dimensionally accurate material. Steel is lighter and to be delivered to site “just in time” for installation. Steel has a long design life and does not deteriorate if properly protected.
Sim (2007)	Construction Speed	HDB using steel instead of concrete to construct lift shafts, which achieved a shortening of construction time by 20%.
Zhang (2008)	Construction Speed Quality	Resulted by a case study on a residential project, using steel instead of RC has achieved a shortening of construction time by 33%. Current steel building may have a good performance on anti-corrosion.

Authors / Year	Parameters	Findings
Aghayere and Vigil (2009)	Construction Speed Safety Quality	Steel structures are easier and quicker to fabricate and erect than RC structures; High ductility enables adequate warning of any impending collapse. The erection of steel structures is not as affected by weather as is the use of RC. Steel is susceptible to corrosion and has to be protected by galvanizing or by coating. Maintenance costs could be higher than RC.

With reference to the indicators addressed in section 2.5.3, as well as the parameters above, following parameters were identified to indicate the differences in the constructability performances of RC frames and steel frames.

- Construction costs. This is included in the category of economic sustainability.

- Labor saving. Labor saving is a main indicator of buildability, identified by BCA (2004).

- Construction speed. The construction speed associated with a structural frame is affected by excavation speed, foundation construction speed, and frame construction speed (see section 3.4).

- Construction safety. It is concluded that steel framed structures have a good construction safety record (Aghayere and Vigil, 2009; Burgan and Sansom, 2006; Silva, 2005). However, whether RC frames or steel frames perform better has not yet been compared by previous studies. This comparison will be done in this research.

- Construction quality. This parameter is addressed by Silva (2005) and Liew (2007).

3.10 Summary

The life cycle processes of RC frame and structural steel frame were reviewed. The differences between the two materials in terms of manufacturing, transportation, maintenance, and end of life stage were identified.

The parameters used to compare the economic sustainability between RC frame and steel frame are: capital costs of constructing structural works, maintenance costs, non-construction costs, end of life costs, and additional incomes. The parameters used to compare the environmental sustainability between RC frame and steel frame are: material consumption, CO_2 emission, water consumption during construction, and noise produced during construction. The parameters used to compare the constructability difference between RC frame and steel frame are: labor saving, construction speed, construction safety, and construction quality.

From the review of previous studies which investigated the performance of economic sustainability, environmental sustainability and constructability of RC framed buildings and SS framed buildings, the knowledge gap is that hitherto, it is not known whether steel or RC framed buildings have better performance in the three areas (environmental and economic sustainability, and constructability) .Firstly the literature review shows that there is no comprehensive economic evaluation model that combines additional costs and additional benefits brought by using SS frame. Secondly, the studies which investigated whether SS framed buildings have better environmental performance than RC framed buildings are inconclusive. Thirdly, no studies have so far been done to compare the constructability performance of these two structural frames in Singapore. Therefore, it is necessary for this study to investigate the performance of economic sustainability, environmental sustainability and constructability of RC framed buildings and SS framed buildings in Singapore.

CHAPTER 4 Conceptual framework for selection of materials for structural frame

4.1 Introduction

This chapter reviews the concepts and theories that are relevant to this research. The relevant theories underpinning economic matters, environmental issues and constructability are identified for the selection of structural material for building frames. After the identification of relevant theories, the hypotheses and sub-hypotheses are set up. Thereafter the conceptual framework is designed.

4.2 Firm's decision on economic matters

4.2.1 The theory of the firm

The period of First World War saw a change of emphasis in economic theory away from industry-level analysis which mainly included analyzing markets to analysis at the level of the firm, as it became increasingly clear that perfect competition was no longer an adequate model of how firms behaved. Economic theory till then had focused on trying to understand markets alone and there had been little study on understanding why firms or organizations exist (Spulber, 2009).

The main tasks of the theory of the firm are to answer these questions (Spulber, 2009):

- Why do firms exist? The theory of the firm shows that firms exist only when they improve the efficiency of economic transactions.

- How are firms established? Individual consumers can choose to become entrepreneurs and establish firms. The theory of the firm thus makes the entrepreneur endogenous in microeconomics.

- What do firms contribute to the economics? Firms are institutions that coordinate transactions by acting as intermediaries.

The theory of the firm incorporates advances in the study of firms from industrial organization, contract theory, game theory, law and economics, institutional economics, the economics of organizations, and finance (Spulber, 2009). Therefore, the theory of the firm helps to clarify management decision making. However, Hall and Hitch (1939) found that executives made decisions by the rule of thumb rather than in a marginalist way.

Transaction cost theory is the foundation of the theory of the firm. Coase (1937) raised the question of why firms exist as functions that are more complex than the firm of conventional pricing theory, as indicated in the traditional theory of the firm. Coase’s (1937) contribution to the modern theory of the firm inspired researchers to investigate the existence of the firms by categorizing organizations into specific market problems. Williamson (1975, 1985) expanded Coase’s contribution and developed transaction cost theory, where the existence of firms is analyzed in economic terms – the transaction costs. To put it succinctly, both Coase (1937) and Williamson (1975, 1985) believed that a firm is an instrument for reducing transaction costs (Schmidt, 2000). The second element in the modern theory of the firm is the theory of agency, which was described by Jesen and Meckling (1976). The agency theory implies that in firms and enterprises, ownership is not always equal to management control. The firm is a legal entity which is at the center of a nexus of contracts (Jesen and Meckling, 1976). These contracts are the agency between ownership and management control. The third building block in the modern theory of the firm is the theory of incomplete contracts. Based on the theory, Grossman and Hart (1986) analyzed the economic factors that have an influence on the decision-making process but do not belong to the category of contracts.

Neoclassical economics is employed to analyze the actions of firms. Newer versions of neoclassical theory often incorporated human awareness of economic criteria changes. Neoclassical economics is therefore still widely used with the following assumptions (Spulber, 2009):

- People have rational preferences among outcomes that can be identified and associated with a value;

- Individuals maximize utility and firms maximize profits.
- People act independently on the basis of full and relevant information.

One characteristic of firms is that firms separate the decision makers of buyers from sellers. As a seller in building development business, a building developer has to consider the consumers' profit and their requirements when planning the building. The relationship between developers and designers is that of buyers and sellers. If design firms aim to sell their design work to developer firms, they have to consider the profit of developer firms and their requirements.

According to the theory of the firm, the following conclusions may be drawn:

- The firm is an efficient organizational form for minimizing transaction costs in building business.
- Both development firms and design firms should consider consumers' utilities.
- The firm is regarded as a profit-maximizing entity whose aims are to react to the changes of inputs and outputs of the market and achieve optimal production (Schmidt, 2000).

4.2.2 Rational choice theory

Rational choice theory, also known as rational action theory, is a framework for understanding and often formally modeling social and economic behavior (Hedström & Stern, 2008). It is the dominant theoretical paradigm in microeconomics. It is also central to modern political science and is used by scholars in other disciplines such as sociology and philosophy.

The 'rationality' described by rational choice theory is different from the colloquial and most philosophical uses of the term. 'Rationality' means in colloquial language 'sane' or 'in a thoughtful clear headed manner'. In Rational Choice Theory 'rationality' simply means that a person reasons before taking an action. In rational choice theory, all decisions are arrived at by a 'rational' process of weighing costs against benefits.

a) Principle

The basic idea of rational choice theory is that patterns of behavior in societies reflect the choices made by individuals as they try to maximize their benefits and minimize their costs (Hedström & Stern, 2008). In other words, people make decisions about how they should act by comparing the costs and benefits of different courses of action. As a result, patterns of behavior will develop within the society as a result of those choices.

The idea of rational choice, where people compare the costs and benefits of certain actions, is easy to see in economic theory. Since people want to get the most useful products at the lowest price, they will judge the benefits of a certain object (for example, how useful is it or how attractive is it) compared to similar objects. Then they will compare prices (or costs). In general, people will choose the object that provides the greatest reward at the lowest cost.

According to Hedström and Stern (2008), rational decision making entails choosing an action given one's preferences, the actions one could take, and expectations about the outcomes of those actions. Actions are often expressed as a set, for example a set of j exhaustive and exclusive actions:

$$A = \{a_1, \ldots, a_i, \ldots, a_j\} \quad \text{………………………..…....... (Eq. 4.1)}$$

b) Assumptions

Although models used in rational choice theory are diverse, all assume that individuals choose the best action according to stable preference functions and constraints facing them. Most models have additional assumptions. Proponents of rational choice models do not claim that a model's assumptions are a full description of reality, but that good models can aid reasoning and provide help in formulating falsifiable hypotheses, whether intuitive or not. Successful hypotheses are those that survive empirical tests.

Rational choice theory makes two assumptions about individuals' preferences for actions:

- Completeness – all actions can be ranked in an order of preference (indifference between two or more is possible).

- Transitivity – if action a1 is preferred to a2, and action a2 is preferred to a3, then a1 is preferred to a3.

These assumptions underpin the concept that given a set of exhaustive and exclusive actions to choose from, an individual can rank them in terms of his preferences, and that his preferences are consistent.

Often, to simplify calculation and facilitate testing, some possibly unrealistic assumptions are made about the world. These include:

- An individual has full or perfect information about exactly what will occur under any choice made. More complex models rely on probability to describe outcomes.

- An individual has the cognitive ability and time to weigh every choice against every other choice. Studies about the limitations of this assumption are included in theories of bounded rationality.

Other assumptions are often incorporated in more complex models, such as the assumption of independence axiom. Also, with dynamic models that include decision-making over time, time inconsistency may affect an individual's preferences.

c) Application

Becker (1978) was an early proponent of applying rational actor models more widely. He won the 1992 Nobel Prize in Economics for his studies of discrimination, crime, and education.

Rationality is widely used as an assumption of the behaviour of individuals in microeconomic models and analysis. Although rationality cannot be directly empirically tested, empirical tests can be conducted on some of the results derived from the models. Over the last decades, rational choice theory has also become increasingly employed in social sciences other than economics, such as sociology and political science (Scott, 1997). It has had far-reaching effects on the study of political science, especially in fields like the study of interest groups, elections, behaviour in legislatures, coalitions, and bureaucracy (Dunleavy, 1991).

4.2.3 Application of theories to economic sustainability

According to the theory of the firm, firms pursue maximum profits. In addition, rational choice theory supports the idea that people will choose the object that provides the greatest reward at the lowest cost. The two theories might explain why economic indicators have to be considered when managers making decisions.

The two theories could be applied in any industry including the construction industry. Firms (developers and construction firms) will pursue economic sustainability when decision makers are selecting building materials.

Therefore, the structural frame that provides the greatest benefit at the lowest life cycle cost will be preferred.

4.3 Firm’s handing of environmental issues

4.3.1 Corporate Social Responsibility – definition and history

The concept of corporate social responsibility (CSR) was initially advocated in the 1950s in the aftermath of World War II. Memories of the Great Depression still loomed large in the public consciousness, and the emphasis lay on ‘taming the excesses of business’ (Green, 2008).

During the late 1960s ‘system thinking’ came into vogue across a wide range of academic disciplines, and CSR was no exception. The notion of social responsibility ‘refers to a person’s obligations to consider the effects of his decisions and actions on the whole social system’ (Davis & Blomstrom, 1966). Also emergent during this period was the notion of a ‘stakeholder approach’, whereby managers are seen to be responsible for balancing the needs of different interest groups. Amongst others, Johnson (1971) contended that business takes place within a 'socio-cultural system'.

An important contribution to the development of CSR was the definition given by Carroll (1979): the social responsibility of business encompasses the economic, legal, ethical and discretionary expectations that society has of organizations at a given point in time. This definition attributes four parts to social responsibility: economic, legal, ethical and discretionary.

In 2000s, there was an increasing tendency to conflate CSR with notions of sustainable development. DTI (2004) defined CSR as being 'about the behavior of private sector organizations and their contribution to sustainable development goals'. CSR was then also associated with a sustainable responsible business (SRB), or corporate social performance (Atkinson, 2000).

Critics argued that corporate social responsibility (CSR) distracts from the fundamental economic role of businesses; Some argued that it is nothing more than superficial window-dressing; Carpenter, Bauer and Erdogan (2009) argued that it is an attempt to pre-empt the role of governments as a watchdog over powerful multinational corporations.

4.3.2 Application of theories to environmental sustainability

Given the impact of construction activity on society, the economy and the environment, and its significance as an employer and provider of work, the construction industry has more reasons to focus on its CSR than most others. Dainty and Murray (2008) published a book to introduce CSR and its application to the construction industry. It is implied that the following issues are involved in the CSR of firms from the construction industry (Dainty & Murray, 2008):

- Developers must buy in to the common goal, commit to delivering high quality attractive place for people to live (ODPM, 2004);
- Contractors should improve built environment;
- Designers should include sustainable development issues into their

design;

- Sustainable development issues should be emphasized in the construction supply chain.
- Building in an environmental friendly way is one aspect of CSR in the construction industry.

According to the theory of corporate social responsibility (DTI, 2004), private sector organizations should contribute to sustainable development goals. Environmental sustainability, as one goal of sustainable development (WRI, 1992), should be addressed as one social responsibility that all private sectors should contribute to. Therefore, the construction sector needs to take charge of its social responsibility of achieving environmental sustainability.

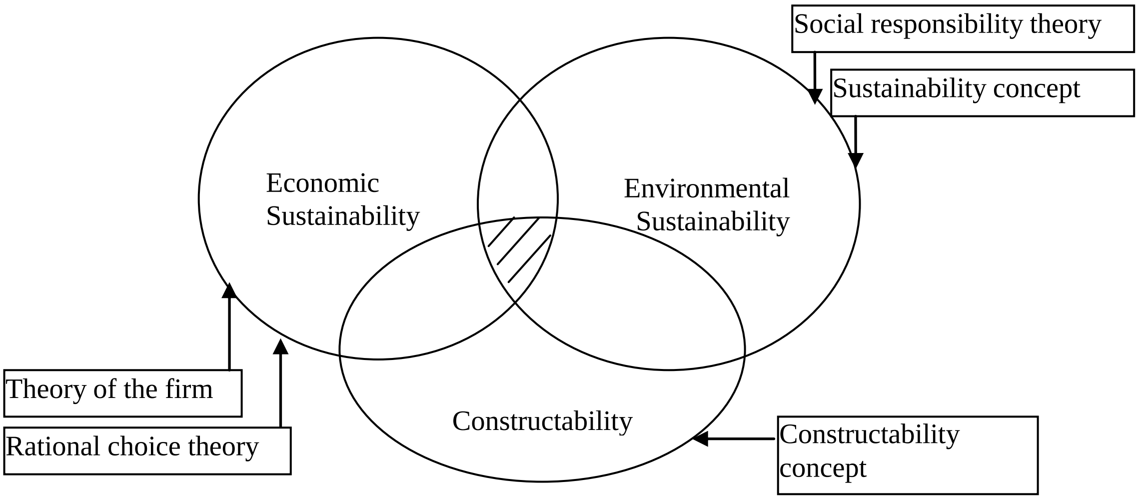
4.4 Firm's need for constructible

The definitions and implications of constructability had been described in Section 2.5.1. Constructability is a system for achieving optimum integration of construction knowledge in the building process and balancing the various project and environmental constraints to achieve maximization of project goals and building performance (CIIA, 1993). The review of the process of constructing structural frame (Section 3.3 to 3.7) shows that a specific structural frame that is selected has unique issues to consider, such as speed of construction, labor usage, safety and quality standards. Therefore, constructability performance is an important consideration when selecting structural materials.

4.5 Research hypotheses

Based on the theories and concepts reviewed in section 4.2 to 4.4, the following hypothesis is set out.

Hypothesis 1- decision making on structural material selection is integrally affected by the material's performance in economic sustainability, environmental sustainability, and constructability.



Note: The shaded area is the optimal decision on material selection.

Figure 4.1 Factors affecting structural material decision (H1)

Based on the factors reviewed in sections 2.3.4 and 3.9.1, it is hypothesized that in the context of RC frame and SS frame:

Hypothesis 2 - Economic performance (EC) associated with structural materials is affected by structural costs (EC1), maintenance costs (EC2), non-construction costs (EC3), end of life costs (EC4) and additional incomes (EC5).

- H2.1 – RC frame has lower structural costs than SS frame.
- H2.2 – RC frame has lower maintenance costs than SS frame.
- H2.3 – RC frame has lower financial costs than SS frame.
- H2.4 – RC frame has higher end of life costs than SS frame.
- H2.5 – RC frame has lower additional income than SS frame.

Based on the factors reviewed in sections 2.4.5 and 3.9.2, it is hypothesized that in the context of RC frame and SS frame:

Hypothesis 3- environmental performance (EN) associated with structural materials is affected by material consumption (EN1), CO_2 emission (EN2), water consumption (EN3), and noise (EN4).

- H3.1 - RC frame has higher material consumption than SS frame.
- H3.2 - RC frame has higher CO_2 emission during construction than SS frame.
- H3.3 - RC frame has higher water consumption than SS frame during construction.
- H3.4 - RC frame produces more noise than SS frame during construction.

Based on the factors reviewed in sections 2.5.3 and 3.9.3, it is hypothesized that in the context of RC frame and SS frame:

Hypothesis 4: The selection of structural materials affects constructability performance (CP) from the aspects of labor saving (CP1), construction speed (CP2), construction safety (CP3) and construction quality (CP4).

- H4.1 - SS frame requires less labor than RC frame.
- H4.2 - SS frame has faster construction speed than RC frame.
- H4.3 - SS frame is safer to construct than RC frame.
- H4.4 - SS frame has higher construction quality than RC frame.

4.6 Conceptual framework

The conceptual framework posits that three constructs, economic sustainability, environmental sustainability, and constructability interact when decisions have to be made on whether to select steel framed structure or RC framed structure. This interaction is shown in figure 4.2. The conceptual framework is supported by the theories discussed in sections 4.2 to 4.4.

Figure 4.2 shows that structural material's economic sustainability is represented by these indicators: Structural costs; maintenance costs (including fire protection costs and corrosion protection costs); non-financial costs (including financial costs and taxes); end of life costs (including disposal costs and demolition cost); and additional income (including benefit of additional useable areas, benefit from flexibility of internal space, and possible incentive from BCA GM and BCA productivity enhancement scheme).

The structural material's environmental sustainability is represented by these indicators: material use (including material recycling rate, material reuse rate, material recyclability, material reusability, and the material waste rate); CO_2 emission; water consumption; and noise during construction (See Figure 4.2).

Finally, Figure 4.2 shows that structural material's constructability performance is represented by these indicators: labor saving; construction speed; construction safety; and construction quality.

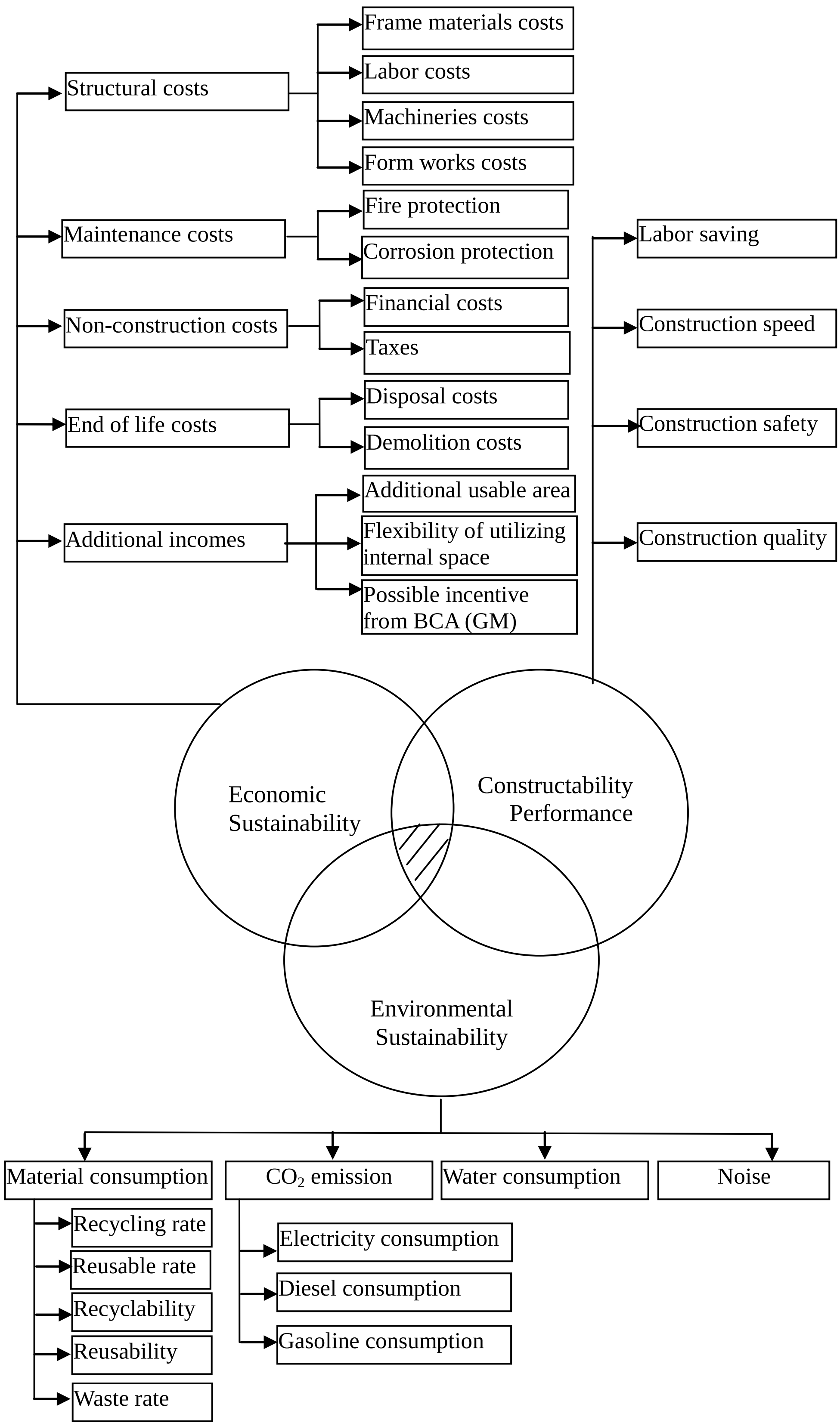


Figure 4.2 Conceptual framework for selection of material for structural frame

4.7 Summary

This chapter reviews three groups of theories/ concepts relating to the selection of material for structural frame.

Firstly, the theory of the firm and rational choice theory are used to explain a firm's economic decision, which leads to economic sustainability. Secondly, Corporate Social Responsibility (CSR) is used to explain a firm's environmental concern when deciding on which frame material should be selected. Finally, the constructability concept is used to explain a firm's need to complete a project expeditiously.

Following the review of the theories/ concepts, four main research hypotheses (H1 to H4) are set out. The conceptual framework for selection of structural frame material is then presented. This framework is tested in the fieldwork.

CHAPTER 5 RESEARCH METHODOLOGY

5.1 Introduction

This chapter presents the research methodology. It starts with a description of the research design adopted, followed by methods and instruments used to collect data. Two categories of data were collected. The first was to ascertain the level of importance of the variables/indicators identified in the conceptual framework. The second was information on performance of RC and SS framed buildings for each indicator.

The next section discusses how the data were analyzed, followed by the method to build the DSSSSM. Finally, the method to validate the DSSSSM is presented.

5.2 Research paradigm and research design

5.2.1 Research paradigm

The most quoted definition of paradigm is Kuhn's (1962) concept in *The Nature of Science Revolution*, and this said concept is the underlying assumptions and intellectual structure upon which research and development in a field of inquiry is based on. Rossman & Rollis (2012) identified four different paradigms and the two primary paradigms are positivist and interpretivist.

- Positivist – associated with quantitative research. Positivist is sometimes referred to as scientific method or science research, is based on the rationalistic and empiricist philosophy (Mackenzie & Knipe, 2006). Positivist may be applied to the social world on the assumption that the social world can be studied in the same way as the natural world, that there is a method for studying the social world that is value free, and that explanations of a causal nature can be provided (Mertens, 2005). Positivists aim to test a theory or describe an experience through observation and measurement in order to predict and control forces that surround us (O'Leary, 2004). Positivists and postpositivist research is most commonly aligned with quantitative methods of data collection and analysis.

- Interpretivist – associated with qualitative research. The interpretivist approaches to researches that have the intention of understanding the world of human experience (Cohen & Manion, 1994), suggesting that reality is socially constructed (Creswell, 2003). The interpretivists tend to rely upon the "participants' views of the situation being studied" (Creswell, 2003, p.8) and recognize the impact on the research of their own background and experiences.

Table 5.1 Summary of positivist and interpretivist

Characteristic	Positivist	Interpretivist
Research goal	Demonstrate causality	Increase general understanding of situation
Research process	Progress made through hypotheses and deduction	Probing rich data to increase understanding
Concepts and variables	Must be operationalized for measurement and quantitative analysis	Should incorporate stakeholder's perspectives
Generalization patterns	Statistical probability	Theoretical abstraction
Research Methods	Quantitative	Qualitative
Sampling requirements	Probability sampling with adequate sampling size	May be non-probability sampling method with a small number of cases for specific reasons

Source: Shrestha (2009)

More recently, research approaches have become more complex in design and more flexible in their application of methods with mixed-methods being more acceptable and common. A mixed-methods approach to research is one that involves gathering both numeric information (for example, on instruments) as well as text information (for example, on interviews) so that the final database represents both quantitative and qualitative information (Creswell, 2003, p.20).

According to Gorard (2004) combined or mixed-methods research has been identified as a "key element in the improvement of social science, including education research" (p.7) with research strengthened by the use of a variety of methods. Many researchers including Creswell (2003), Thomas (2003) and Krathwohl (1993) now view qualitative and quantitative methods as complementary method/s for the investigation. While some paradigms may appear to lead a researcher to favour qualitative or quantitative approach, in effect no one paradigm actually prescribes or prohibits the use of either methodological approach. However, this may not sit comfortably with researchers who are strongly aligned with a particular research approach. Almost inevitably in each paradigm, if the research is to be fully effective, both approaches need to be applied. It is unduly impoverished research, which eschews the use of both qualitative and quantitative research approaches. Paradigms, which overtly recommend mixed methods approaches which allow collecting both quantitative and qualitative data and integrating the data at different stages of inquiry (Creswell, 2003).

This study explores the factors which influence the selection of structural frame materials and investigates the performance of RC-framed buildings and SS-framed buildings. Due to the complex nature of this study, there is no single paradigm that could satisfactorily deal with all of the required methodological aspects. Therefore, it is necessary to combine the quantitative/positivist paradigm with the qualitative/interpretivist paradigm. The blending of both paradigms provided the researcher with the ability to statistically analyze the scientific data whilst also recognizing the complex sustainability and constructability factors that influence selection of structural frame materials.

5.2.2 Research design

A literature review was conducted to discover existing knowledge on the subject, determine how this study differs from existing works, and to establish how to further add to the knowledge in the area. The review is also helpful for enabling the researcher to conceptually frame the work (Alston & Bowles, 2012).

The contents of the literature review encompassed four aspects: foundational theories, contextual information, relative practical frameworks, and practical experiences. Based on the literature review, the hypotheses were developed (see Section 4.5) and the conceptual framework was established (see Section 4.6).

There are six common types of research design:

- **Case study**. A Case study is appropriate for in-depth understanding of particular instances. It will not be an advantageous method to answer a research question in a form of “how many” or “how much” line of inquiry (Yin, 2009).

- **Survey**. A survey is suitable for obtaining broad population characteristics (Rea & Parker, 2005). It is favoured to identify a research question in a form of “how many”, “how much” or some types of “what” (Yin, 2009).

- **Experiment**. Experiments are used to test cause and effect relations between different variables through various forms of control (Ibrahim, 2003).

- **Correlation or regression analysis**. This analysis is used when experimental control is difficult or impossible (Tan, 2004).

- **Comparative research**. Comparative research seeks to explain the differences that have occurred between two or more groups (Hollway & Jefferson, 2000).

- **Historical research**. Historical research seeks to explain the past in order to understand or draw lessons for the present and future (Kumar, 2011).

The current research aims to investigate decision makers' perceptions of the impacts of pre-addressed factors and attributes on the selection of structural frame materials. Among the six types of research design methods, a survey is the most appropriate tool for achieving the research aim of this study because a survey reflects the attitudes and beliefs of respondents (Royse, 2008) and is effective in collecting information from the population (Tan, 2004).

5.3 Data collection

5.3.1 Sampling

The population for this study is all RC-framed buildings and all SS-framed buildings constructed in Singapore. As no official document listing all the RC and SS projects exists in Singapore, the sampling frame of this study is narrowed down into:

- RC-framed building projects completed from 2009 to 2011 and constructed by A1 and A2 contractors (registered by BCA in 2011) in Singapore. The minimum paid up capital for A1 and A2 firms are S$15 million and S$6.5 million respectively. The tendering limit of contractors with A1 financial grade is unlimited and the tendering limit of contractors with A2 financial grade is $85 million; and

- SS-framed building projects completed after 2001 and undertaken by those builders with SS work licenses in Singapore.

As most buildings in Singapore have RC frames, only those completed in the last three years were considered. The lack of SS framed buildings made it necessary for this research to consider buildings completed in the past 10 years.

As most of the information required by this study should be provided by contractors, all BCA registered A1and A2 building contractors were contacted by telephone and email to check if they had constructed an RC building and to determine whether they would be willing to participate in this survey. All SS contractors were contacted as well to identify whether they had constructed a SS building in the past ten years and whether they would be willing to participate in this survey. Contractors' contact information was obtained from the BCA website.

5.3.2 *Data collection method*

The information on each project was collected by interviewing a group comprising two to three experts involved in that project. In order to obtain comprehensive information on each project, these experts were drawn from a multi-discipline pool of contractors, architects, and engineers. As the data to be collected are complicated, extensive communication was required. Therefore, face-to-face interviews using a structured questionnaire were conducted so that extensive explanations can be provided to the participants. This also helped respondents not to misinterpret the questions. The interviews were conducted primarily in English or Mandarin, based on the respondents' preference. In addition, another purpose of using face-to-face interviews is to ensure that questions from some participants could be answered immediately.

Those contractors willing to participate in the study normally provided the contact information for the project managers for the projects about which the contractors wished to provide data for the study. The project managers were then contacted to make interview appointments; they were also asked to refer designers and clients who had been involved in same project. Although ideally designers and clients attended the interview, most of the questionnaires were completed by separately interviewing experts from contractors, designers, and clients because many of them were not able to schedule a single interview together.

Calls had been made to identify respondents who were willing to the participant in this survey. An appointment of interview was made at least 3 days prior to the interview. Then questionnaires were sent to respondents when making appointments with them so that participants have enough time to review documents. To ensure the respondents complete the survey properly, in the first paragraph of this section, it was explained that face-to-face interviews using a structured questionnaire were conducted. For some participants who stated that they needed to check project documents to answer some questions after the interview, up to three reminder telephone calls were made to them.

In order to ensure that the survey results are rigorous and reliable, the following strategies were adopted: 1) Respondents were randomly selected from the sampling frame to minimize bias. They were given the choice to participate in the study or not, so there are no unwilling and ineffective subjects; 2) The data for each project were obtained from contractors, consultants and clients and not just from one source to ensure that the responses are reasonably accurate; 3) Face-to-face interviews using a structured questionnaire were conducted so that extensive explanations can be provided to the participants. This also helped respondents not to misinterpret the questions. The interviews were conducted primarily in English or Mandarin, based on the respondents' preference. 4) Incomplete questionnaires were excluded.

5.3.3 Data collection instrument

During the pilot study stage, it was discovered that project managers and QS from contractors have the first hand data which were requested in this study. All of the actual data requested in the survey were provided by project managers and QS from contractors of those investigated projects according to previous documents.

For each project, data were collected from different parties involved in the project (see Table 5.2). Respondents were asked to complete the questionnaires based on an actual project.

Table 5.2 Parties involved in providing data for each project

Factors	Criteria/indicators	Respondent
Economic sustainability (EC)	EC1: Structural costs	Contractors
	EC2: Maintenance costs	Contractors
	EC3: Non-construction costs	Clients
	EC4: End of life costs	Demolition contractors
	EC5: Additional income	Designers
Environmental sustainability (EN)	EN1: Material consumption	Contractors
	EN2: CO_2 emission	Contractors
	EN3: Water consumption during construction	Contractors
	EN4: Noise	Contractors
Constructability performance (CP)	CP1: Labor consumption	Contractors
	CP2: Construction duration	
	CP3: Construction safety	
	CP4: Construction quality	

As respondents are not expected to be equally familiar with both steel and concrete construction, they answered questions relating to one of the construction which they are familiar with, and not both types of construction. For this reason, separate questionnaires were developed to collect data from SS builders and contractors of RC framed buildings. Four questionnaires were designed (see Appendices 1 to 4). The questionnaires in Appendices 1 and 2 were used to collect data from contractors who constructed RC and SS projects, respectively. The questionnaire in Appendix 3 was employed to collect data from designers; information on additional income (EC5) and preference data were collected to develop the weighting system of the DSSSSM. The questionnaire for demolition contractors (Appendix 4) was used to collect data on end-of-life costs (EC4) if EC4 was found to be an important criterion (see Section 6.3).

The terms used in the survey had been refined during the pilot study stage to weed out ambiguous phrases. Definitions of terms provided in next page were explained to respondents when conducted face to face interview.

The questionnaires for contractors (Appendices 1 and 2) comprised three parts.

Part A: General information on respondent and project

In this section, interviewees were asked to provide their names (optional) and information on their work experience. They were also asked to provide information on a completed RC or SS project in which they were involved. Information sought included characteristics of the project, total gross floor area, height of the building, project type, project duration, and so on.

Part B: Performance information of project

The objective of this section is to measure the performance of the project. Interviewees were asked to provide information on the following:

- Structural cost (EC1). This is the final costs including variations of the structural frame works.
- Maintenance cost (EC2). This includes the costs of maintenance fireproofing system and anti-corrosion system.
- Recycling rate (EN1.1). This is the percentage of recycled material used against total material consumption.
- Reuse rate (EN1.2). This is the percentage of reused material used against total material consumption.
- Recyclability (EN1.3). This is the proportion of recyclable structural material in the end of life stage.
- Reusability (EN1.4). This is the proportion of reusable structural material in the end of life stage.
- Waste rate (EN1.5). This is the percentage of material wasted against total material consumption.

- Energy consumption including electricity, diesel, and gasoline consumption in the construction stage (EN2).

- Water consumption (EN3). This is the amount of water consumption during construction.

- Severity of noise during construction (EN4).

- Labor consumption (CP1). This is the amount of water consumption during construction.

- Construction duration (CP2)

- Construction safety (CP3). This is measured by the Accident Severity Rate.

- Construction quality (CP4). This is measured by the structural CONQUAS score.

The questionnaire for designers and clients (Appendix 3) included three parts.

Part A: General information on respondent and project

Part A of this questionnaire is same as part A of the questionnaire for contractors (Appendices 1 and 2).

Part B: Performance information of project

The objective of this section is to measure the performance of the project. Interviewees were asked to provide information on the following:

- Proportion of loan and average loan period (EC3.1)

- Taxes (EC3.2)

- Additional usable area (EC5.1). This is the proportion of sectional area of columns over the GFA of a standard level.

- Flexibility of internal space using (EC5.2)

Part C: The importance of each criterion and attribute

- Participants were asked to do a pair-wise comparison between two factors (for example, X and Y) on a 9-point scale (1 = “the two factors have equal importance”; 3 = “one factor has a weaker importance than the other”, 5 = “one factor is of greater importance than the other”, 7 = “one factor has demonstrated importance over the other”, and 9 = “one factor has absolute importance over the other”). The details of the scale are shown in Table 5.3.

Table 5.3 Pair-wise comparison based on 1-9 scale

X	Importance																	Y
	X is more important extremely ←								equal important	Y is more important → extremely								
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Economic sustainability																		Environmental sustainability
Economic sustainability																		Constructability
Environmental sustainability																		Constructability

- Participants were asked to rate the priority level of each criterion and attribute using a 5-point Likert scale (1= “extremely not important” and 5= “very important”) when they propose a structural frame to their clients (see Table 5.4).

Table 5.4 Priority investigation of criteria and attributes

Criteria and attributes	**Priority** (Scale 1-5)
EC: Economic sustainability	
EC1: Structural costs (including costs of materials, machinery, manpower)	
EC2: Maintenance costs (fire protection, corrosion protection) in operation stage	

Criteria and attributes	Priority (Scale 1-5)
EC3: Non-construction costs	
EC3.1: Financial cost	
EC3.2: Taxes	
EC4: Disposal and demolition costs at the end of building's life	
EC5: Potential incomes earned by structural materials	
EC5.1: Increased area by optimizing structural frame (such as smaller beams and columns)	
EC5.2: Flexibility of internal space using	
EC5.3: Incentives that client might obtain from government	
EN: Environmental sustainability	
EN1: Material reduction such as by using recycled materials and/or reuse structural elements	
EN1.1: Material recycling rate	
EN1.2: Material reuse rate	
EN1.3:Material recyclability (the potential that the structural materials can be recycled for future use)	
EN1.4: Material reusability (the potential that the structural materials can be reused for subsequent project)	
EN1.5: Material waste rate on site	
EN2: CO_2 emission/ energy consumption during construction	
EN3: Water consumption during construction	
EN4: Noise pollution during construction	
CP: Constructability	
CP1: Labor saving during construction	
CP2: Construction duration	
CP3: Construction safety	
CP4: Construction quality	
Others (please state and rate):	

Participants were also allowed to suggest other attributes that they considered important but were not included in this questionnaire.

The questionnaire for demolition firms (Appendix 4) included Part 1 of questionnaires 1 and 2 (for contractors of RC and SS projects). It also asked about the average demolition cost of RC projects.

5.4 Data Analysis methods

5.4.1 Determining importance of attributes and factors: t-test

The *t*-test of the mean was conducted to determine if each attribute and factor are important using the Statistical Package for Social Science (SPSS) software. The null and alternative hypotheses are as follows.

H_0: $\mu=3$

H_1: $\mu\neq3$

"3" was chosen as it represents the point of neutrality on the 5-point Likert scale (the "neutral" option); thus, any deviation from 3 demonstrates an inclination toward important (>3) or not important (<3). If μ is less than 3, it means the corresponding attribute is not important when determining the selection of structural frame material. H_0 will be rejected if the value of significance at the 95% confidence level is less than 0.05 and the *t* value is negative.

5.4.2 Describing the performance of RC and SS projects: Boxplots

In descriptive statistics, a boxplot (also known as a box-and-whisker diagram or plot) is a convenient way of graphically depicting groups of numerical data through their five-number summaries: the smallest observation (sample minimum), lower quartile (Q1), median (Q2), upper quartile (Q3), and largest observation (sample maximum). A boxplot can also indicate which observations, if any, might be considered outliers.

Box-and-whisker plots are uniform in their use of the box: The bottom and top of the box are always the 25^{th} and 75^{th} percentile (the lower and upper quartiles, respectively) while the band near the middle of the box is always the 50^{th} percentile (the median).

The boxplots method was used in this study because it has several strengths.

Boxplots graphically display a variable’s location and spread at a glance; therefore, they are a quick way of examining one or more sets of data graphically. Boxplots also provide some indication of the data’s symmetry and skewness. In addition, unlike many other methods, boxplots show outliers. Finally, boxplots take up less space and are therefore particularly useful for comparing distributions among several groups or sets of data.

5.4.3 Compare the difference between RC and SS projects

Normally, Levene’s test, as a parameter test, is preferred to do a statistic comparison of two groups because it provides more accurate result than non-parameter test. One important assumption of using Levene’s test is that the two groups should have same distribution. According to the central limit theorem, the RC group is normal distribution because of the sample size of 30. Therefore, the one-sample Kolmogorov-Smirnov test was conducted to determine if the distribution of the SS group is normal. If it is normal, Levene’s test will be conducted to investigate if the difference between the RC group and SS group is significant. If it is not normal, the Kolmogorov-Smirnov test will be used to investigate the difference.

The method of testing the differences between RC and SS projects is depicted in Figure 5.1.

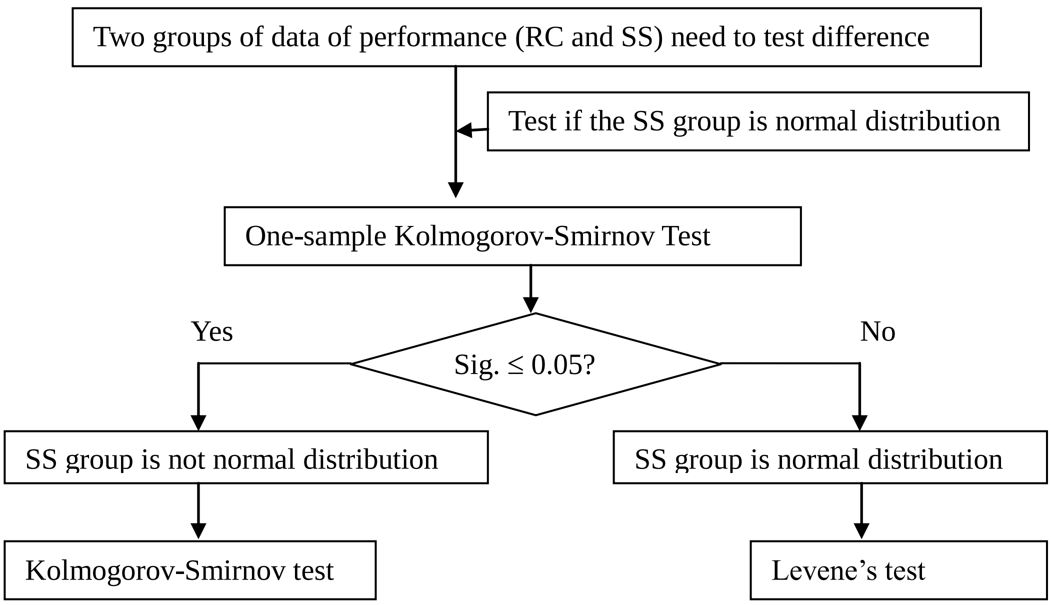


Figure 5.1 Testing the difference between RC and SS projects

5.4.3.1 Levene's test and unpaired t-test

The parametric test and the non-parametric test are two methods used for checking the difference between two groups of different sample sizes. Levene's test was used as it is the most popular method among parametric tests and is applicable regardless of whether the variances of the two groups are equal or not. However, one limitation of Levene's test is that the two groups must have the same distribution. The non-parametric test is an appropriate method to use when the two groups have a different distribution.

Levene's test (Levene 1960; NIST 2006) was performed at the 0.05 significance level to check if samples have equal variances (i.e., homogeneity of variance). The null hypothesis is that population variances of the two groups are equal. If the null hypothesis is rejected, the alternative hypothesis is accepted, indicating that one population variance is different from the other.

The two-sample *t*-tests for verifying the difference in mean, if any, can be either unpaired or paired. Paired *t*-tests are a form of blocking and have greater power than unpaired tests when the paired units are similar with respect to "noise factors" that are independent of membership in the two groups being compared (Rice, 2006). The unpaired, or "independent samples," *t*-test is used when two separate sets of independent and identically distributed samples are obtained, one from each of the two populations being compared.

In this study, the unpaired *t*-test for equality of means was conducted to check if the two groups (RC and SS) have equal means with regard to each attribute. The test process is shown in Figure 5.2.

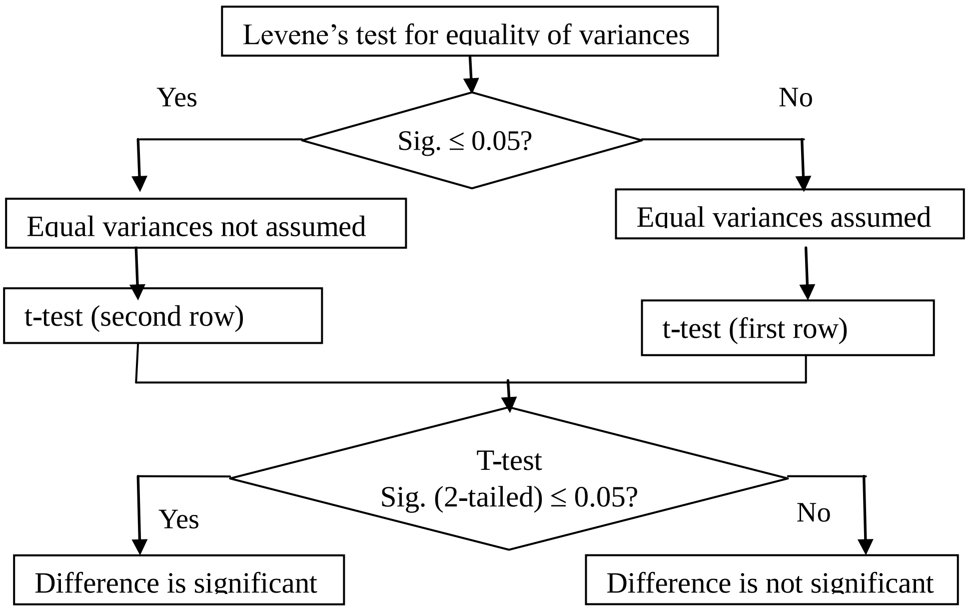


Figure 5.2 Levene's test and t-test procedure for equality of means

5.4.3.2 Kolmogorov-Smirnov Test

As a non-parametric test, Kolmogorov-Smirnov test is widely used to test the difference between the two groups with a different distribution.

5.5 DSSSSM construction method

5.5.1 Multiple criteria decision making (MCDM)

Traditionally, corporate decision making has revolved around one objective: profit maximization (Diekmann, 1981). Indeed, the majority of current selection methods exhibit constraint and an overreliance on the principle of acceptance of the lowest bid (Holt et al., 1993). In contrast, comprehensive evaluation of structural frames should consider a frame's all-round performance potential as the conceptual framework (see Figure 4.2) has shown that there are multiple factors and indicators. However, such evaluation can be difficult to perform, as it is characterized by many decision parameters (economic matters, environmental issues and constructability objectives) and several outcome dimensions (decision alternatives). Fortunately, a technique exists in various forms for such analysis.

Termed Multiple Criteria Decision Making (MCDM), the method refers to the making of decisions in the face of uncoupled, multiple decision criteria (Mohseli & Martinelli, 1990). It is an operational evaluation and decision support approach that is suitable for addressing complex problems featuring high uncertainty, conflicting objectives, different forms of data and information, multiple interests and perspectives, and the accounting for complex and evolving biophysical and socio-economic systems (Latham, 1993).

MCDM problems are commonly categorized as continuous or discrete, depending on the domain of alternatives. Hwang and Yoon (1981) classified them as: (i) Multiple Objective Decision Making (MODM), with decision variable values to be determined in a continuous or integer domain, of infinite or large number of choices, to best satisfy the decision making constraints, preferences or priorities; and (ii) Multiple Attribute Decision Making (MADM), with discrete, usually limited, number of pre-specified alternatives, requiring inter and intra-attribute comparisons, involving implicit or explicit tradeoffs.

MODM is a problem-solving technique in which the objectives (decision alternatives) are not predetermined, and it is therefore commonly used for design (that is, design the best option in respect of purchaser objectives). Such an approach is unrealistic for structural frame material selection because the cost of accruing 'perfect' (design/evaluation) data would be unacceptably high. Evaluation should not make informational demands in excess of data commonly available (Diekmann, 1979). Furthermore, MODM is infeasible, as a 'perfect' solution would be practically impossible to find and would be likely to prove inordinately expensive. For these reasons MODM is not considered further in this study.

Conversely, MADM is capable of helping to select (identify) optimum choice in respect of the same objectives where the decision alternatives are predetermined (Holt et al., 1994). Hence it is suitable for the multi criteria nature of this selection problem.

Various MADM techniques have been developed. The frequently used techniques are: Analytic hierarchy process (AHP); Analytic network process (ANP); Fuzzy methodology; Ideal point method such as TOPSIS; and Multiple Attribute Value Technique (MAVT).

The AHP is a structured technique for organizing and analyzing complex decisions. Based on mathematics and psychology, it was developed by Saaty in the 1970s and has been extensively studied and refined since then (Saaty, 2008). The ANP is a more general form of the AHP used in multi-criteria decision analysis. AHP structures a decision problem into a hierarchy with a goal, decision criteria, and alternatives, while the ANP structures it as a network (Saaty and Vargas, 2006). Both then use a system of pairwise comparisons to measure the weights of the components of the structure, and finally to rank the alternatives in the decision (Saaty, 1996).

AHP and ANP are not suitable for this study because of too many criteria and attributes. Participants would be confused when they do the paired-wise comparison when there are too many criteria.

Fuzzy sets were introduced by Zadeh (1965) as an extension of the classical notion of sets. Kuzmin (1982) used fuzzy sets in decision-making area. Thereafter, this idea is used now in many MCDM algorithms to model and solve fuzzy problems.

Fuzzy methodology is not suitable for this study because it causes rank disagreements and produces less consistent results (Buede and Maxwell, 1995) and does not have a unique method to derive importance weights.

The Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) is a multi-criteria decision analysis method, which was originally developed by Hwang and Yoon (1981) with further developments by Yoon (1987), and Hwang et al. (1993). TOPSIS is based on the concept that the chosen alternative should have the shortest geometric distance from the positive ideal solution and the longest geometric distance from the negative ideal solution. It is a method of compensatory aggregation that compares a set of alternatives by identifying weights for each criterion, normalising scores for each criterion and calculating the geometric distance between each alternative and the ideal alternative, which is the best score in each criterion.

TOPSIS relies on the assumption that the criteria are monotonically increasing or decreasing (Yoon, 1987). This method suffers from the low participation of decision makers because the information of decision maker's subjective preferences is not considered (Hwang, et al., 1993). TOPSIS is not suitable for this study because the criteria and indicators are not always monotonically increasing or decreasing, and the decision maker's preferences should be considered in the selection of structural material.

The MAVT method allows decisions with multiple attributes to be made by developing a scoring system. It involves three steps: ascertaining importance weights of each attribute; rating an option (RC frame or SS frame) against each attribute; and aggregating the weights with the rates.

MAVT is suitable for this study because it gives more consistent rankings (Ling, 1999) and the scores derived from the MAVT system enable structural frames to be ranked. This method is also adopted because it allows multiple attributes to be considered, and is a quantitative approach and hence rationalised decision-making to identify suitable structural frame can be carried out.

5.5.2 MAVT- Weighting method

The first step of MAVT is to ascertain the importance weights of the various criteria and attributes. Weights reflect the ranking of each factor and attribute. The decision hierarchy in Figure 5.3 shows that there are three levels of weight that need to be determined.

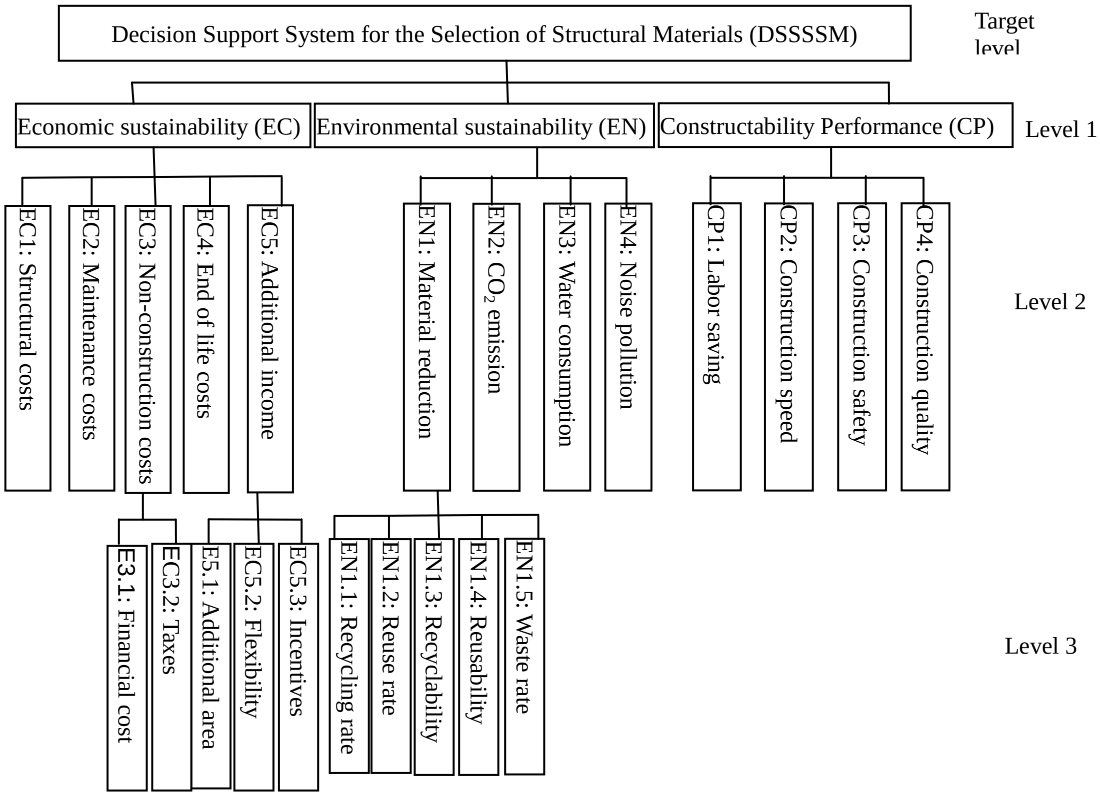


Figure 5.3 Decision hierarchy of DSSSSM

5.5.2.1 Determining weights of level 1 factors – AHP

The weights of the three factors (EC, EN and CP) make up the first-level (see Figure 5.3). The first-level weights are obtained by using Saaty's Analytic Hierarchy Process (AHP) technique (Saaty, 2005). The participants were asked to compare each factor against all the others based on Saaty's 1–9 point scale using the pair-wise comparison method to establish their relative importance (see section 5.3.3). These pair-wise comparisons are: EC against EN; EC against CP; and EN against CP. In Saaty's 1–9 point scale method, 1 means equal importance between the pairs while 9 means one criterion has absolute importance over the other criterion in the pair-wise comparison. In order to minimize the possibility of bias, all participants were asked to rank each factor based on their experience and objective judgment. All the data from the pair-wise comparison were used to compute the weights of the first-level factors (ω_i) based on the following procedure.

- Build consolidated AHP input matrix (A)

By conducting a pair-wise comparison of the three factors, the data from each participant (Table 5.2) were transformed into an original AHP input matrix (A_k)

$$A_k = \begin{bmatrix} 1 & \alpha_{12k} & \alpha_{13k} \\ \alpha_{21k} & 1 & \alpha_{23k} \\ \alpha_{31k} & \alpha_{32k} & 1 \end{bmatrix}, \quad (k = 1,2,\dots,39) \text{........................ (Eq. 5.1)}$$

where α_{ijk} is the relative importance of factor $\mathbf{i}$ against $\mathbf{j}$ from the $\mathbf{k}$ th participant.

Then, the 39 original AHP input matrixes were consolidated into one AHP input matrix ($\mathbf{A}$) by calculating the geometric mean of each vector α_{ij} (refer to Equation 5.2).

$$\alpha_{ij} = (\alpha_{ij1} * \alpha_{ij2} * \cdots * \alpha_{ijk})^{\frac{1}{k}} \text{.................................... (Eq. 5.2)}$$

- Normalize the matrix A to | A |

The consolidated AHP input matrix $\mathbf{A}$ was normalized using Equation 5.3.

$$|A| = \begin{bmatrix} 1/S_1 & \alpha_{12}/S_2 & \alpha_{13}/S_3 \\ \alpha_{21}/S_1 & 1/S_2 & \alpha_{23}/S_3 \\ \alpha_{31}/S_1 & \alpha_{32}/S_2 & 1/S_3 \end{bmatrix} \text{.................................. (Eq. 5.3)}$$

where $\mathbf{S_j}$ is the sum of column $\mathbf{j}$ of | A | (refer to Equations 5.4 to 5.6)

$$S_1 = 1 + \alpha_{21} + \alpha_{31} \text{... (Eq. 5.4)}$$

$$S_2 = \alpha_{12} + 1 + \alpha_{32} \text{... (Eq. 5.5)}$$

$$S_3 = \alpha_{13} + \alpha_{23} + 1 \text{... (Eq. 5.6)}$$

- Calculate Eigen vectors

Eigen vectors were derived by dividing the sum of each row of | A | by 3.

$$\omega_i = \text{Eigen vector } \varepsilon_1 = \begin{bmatrix} \sum \text{row1}/_3 \\ \sum \text{row2}/_3 \\ \sum \text{row3}/_3 \end{bmatrix} = \begin{bmatrix} \omega_1 \\ \omega_2 \\ \omega_3 \end{bmatrix} \quad \text{.........} \quad \textit{(Eq. 5.7)}$$

Then, the normalized matrix was squared and the Eigen vectors ε_2, and ε_3 were calculated.

The largest eigen value: $\lambda = s_1\varepsilon_1 + s_2\varepsilon_2 + s_3\varepsilon_3$......... *(Eq. 5.8)*

- Verify consistency

Finally, the consistency was verified by checking the consistency ratio (CR). If the consistency ratio was less than 0.1, the consistency was considered acceptable (Saaty and Vargas, 2006).

CR = the consistency index （CI） / Random Index (RI) ..... *(Eq. 5.9)*

where CI = (λ- n) / (n-1), and RI = 0.66 when n=3.

5.5.2.2 Determining weights of level 2 and 3– Likert scale

It was not practical to use the AHP technique to obtain the weights of those attributes on levels 2 and 3 due to their large numbers. Therefore, a 1–5 Likert scale was used to investigate the weights of the attributes in the second and third levels, where 1 means “not important”, 3 means “neutral” and 5 means “very important”. All the respondents were asked to indicate the extent to which each attribute contributes to the selection of structural frame material.

The weight for each attribute (ω_{ij}) was obtained using the Equation 5.10:

$$\omega_{ij} = a_{ij}\omega_i \quad \text{……………………………..........} \quad \textit{(Eq. 5.10)}$$

where a_{ij} is the weight of attribute j under factor i .

$$a_{ij} = \frac{a_j}{\sum_{j=1}^{m} a_j} \quad \text{……………………………………………..} \quad (Eq.\ 5.11)$$

$$a_j = \frac{1(n_1)+2(n_2)+3(n_3)+4(n_4)+5(n_5)}{n_1+n_2+n_3+n_4+n_5} \quad \text{…………………………..} \quad (Eq.\ 5.12)$$

where a_j is the mean importance rating of an attribute. n_1, n_2, n_3, n_4, and n_5 are the numbers of subjects who rated the attributes as 1, 2, 3, 4, and 5. j is the attribute reference and there are m numbers of attributes under factor i.

5.5.3 MAVT- Rating method

The second step of the MAVT is to rate an option (RC frame or SS frame) against each attribute. This entails getting decision makers to assign a score to each attribute in an objective manner. The different methods of rating are presented below.

5.5.3.1 Method 1: Quartiles and linear interpolation

- Quartiles

Quantiles are points taken at regular intervals from the cumulative distribution function of a random variable (Hyndman & Fan, 1996). Dividing ordered data into q essentially equal-sized data subsets is the motivation for q-Quantiles; Quartiles are the data values marking the boundaries between consecutive subsets. Some q-Quantiles come with special names. For example, the 3-Quantiles are called tertiles or terciles, and the 4-Quantiles are called quartiles.

The quartiles of a set of values are the three points that divide the data set into four equal groups, each representing one fourth of the population being sampled.

First quartile (designated Q1) = splits lowest 25% of data = 25th percentile

Second quartile (designated Q2) = cuts data set in half = 50th percentile

Third quartile (designated Q3) = splits highest 25% of data, or lowest 75%

= 75th percentile.

Fourth quartile (designated Q4) = all data = 100th percentile

In this study, quartiles were adopted because they are useful measures as they are less susceptible to long-tailed distributions and outliers (McNamara, 2007). Empirically, if the data being analyzed are not actually distributed according to an assumed distribution or if there are other potential sources for outliers that are far removed from the mean, quartiles can result in more useful descriptive statistics than means and other moment-related statistics.

The upper and lower hinges are descriptive statistics of the position of the first and third quartiles from a sample size *n* (in this study, n = 39). The values at the bottom legs are called the hinges H_1 and H_3. The central peak (H_2) is the statistical median. To obtain the hinges, every set of data indicating the performance of each attribute is reordered in an ascending order. Then, the method provided by Tukey (1977) and Moore and McCabe (2002) is used to locate the hinges (Equations 5.13 to 5.15).

$$H_1 = P_{ij(\frac{n+1}{4})} \quad \text{……………………………} \quad \text{(Eq. 5.13)}$$

$$H_2 = P_{ij(\frac{n+1}{2})} \quad \text{……………………………} \quad \text{(Eq. 5.14)}$$

$$H_3 = P_{ij(\frac{3n+1}{4})} \quad \text{……………………………} \quad \text{(Eq. 5.15)}$$

where P_{ijk} is the performance value of j^{th} attribute under i^{th} criteria of k^{th} project (after reordering).

The hinges of each attribute are written out in the shape of a "w" as illustrated in Figure 5.4.

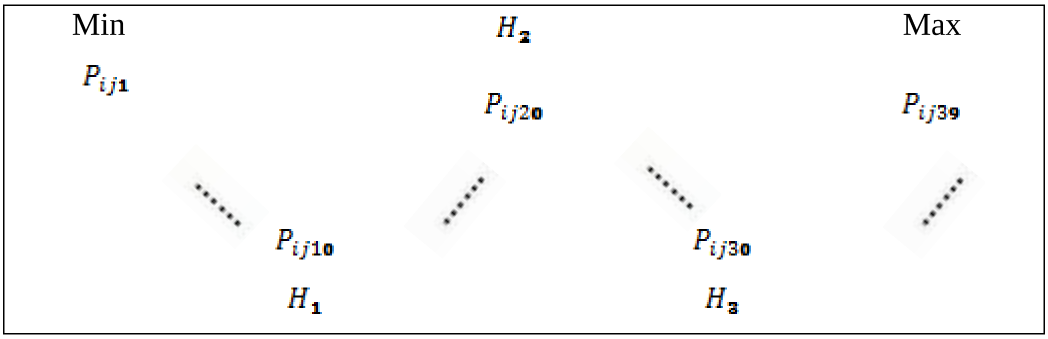


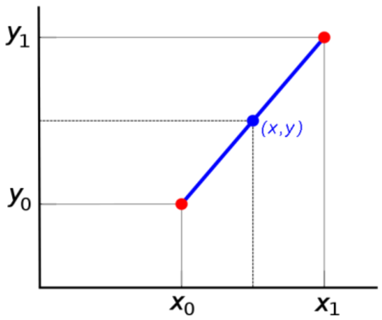
Figure 5.4 Location of hinges

After the statistical analysis, the performance values of each attribute were classified into four groups using the quartiles method.

- Linear interpolation

Linear interpolation is a method of curve fitting using linear polynomials. It is often used to approximate a value of some function *f* using two known values of that function at other points (Hazewinkel, 2001).

If the two known points are given by the coordinates (x_0, y_0) and (x_1, y_1), the linear interpolation is based on the assumption of a straight line between these points. For a value *x* in the interval (x_0, x_1) with a positive slope (Figure 5.5), the value *y* along the straight line is derived geometrically from Figure 5.3 and the Equations 5.16 and 5.17.

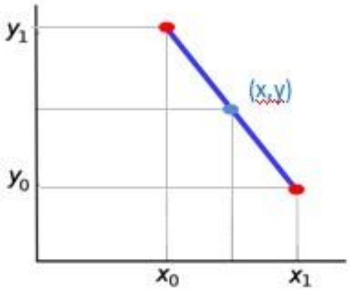


$$\frac{y-y_0}{x-x_0} = \frac{y_1-y_0}{x_1-x_0} \quad \text{.......... } \textit{(Eq. 5.16)}$$

$$y = y_0 + \frac{y_1-y_0}{x_1-x_0}(x - x_0) \quad \text{.. } \textit{(Eq. 5.17)}$$

Figure 5.5 Linear interpolation calculation (positive slope)

For a value *x* in the interval (x_0, x_1) with a negative slope (Figure 5.6), the value *y* along the straight line is derived from the Equations 5.18 and 5.19.



$$\frac{y_1 - y}{y_1 - y_0} = \frac{x - x_0}{x_1 - x_0} \text{ ……………… } \textit{(Eq. 5.18)}$$

$$y = y_1 - \frac{y_1 - y_0}{x_1 - x_0}(x - x_0) \text{ ….. } \textit{(Eq. 5.19)}$$

Figure 5.6 Linear interpolation calculation (negative slope)

- Quartiles and linear interpolation

In this study, a score of 0–100 was used to rate each attribute. In order to build a rating function for those attributes measured by accurate data (such as EC1, EC2, and so on.), the quartiles method was firstly used to divide the 39 sets of data into four groups, each with an equal score range of 25.

However, it will not be reasonable if the same score is given to the attributes located in the same group because the range of one group might be huge. It is assumed that the score is linearly earned between the hinges. The method of linear interpolation is then used to rate the attributes with a performance value located between the hinges. Figure 5.7 shows that the attribute with the larger performance value earns a lower score. For example, if the value of structural costs (EC1) of a project is very high, its performance is not good. Hence, the score rated by EC1 will be low.

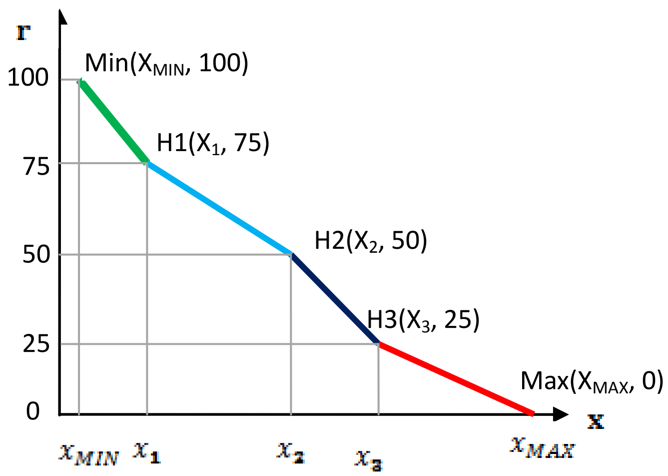


Figure 5.7 Rating functions (negative slope)

Based on Equation 5.19, the rating function is given in Equation 5.20

$$r_{ijk} = \mathrm{f(x)} = \begin{cases} 100,\ \ and x \in (0, \mathrm{x_{MIN}}) \\ 100 - 25 * \frac{\mathrm{x - x_{MIN}}}{\mathrm{x_1 - x_{MIN}}},\ \ and x \in (\mathrm{x_{MIN}}, \mathrm{x_1}) \\ 75 - 25 * \frac{\mathrm{x - x_1}}{\mathrm{x_2 - x_1}},\ \ and x \in (\mathrm{x_1}, \mathrm{x_2}) \\ 50 - 25 * \frac{\mathrm{x - x_2}}{\mathrm{x_3 - x_2}},\ \ and x \in (\mathrm{x_2}, \mathrm{x_3}) \\ 25 - 25 * \frac{\mathrm{x - x_3}}{\mathrm{x_3 - x_{MAX}}},\ \ and x \in (\mathrm{x_3}, \mathrm{x_{MAX}}) \\ 0,\ \ and x \in (\mathrm{x_{MAX}}, \infty) \end{cases} \quad \ldots\ldots\ldots \textit{(Eq. 5.20)}$$

where r_{ijk} is the rating score given to the k th attribute under j th criteria, under i factor.

Figure 5.8 shows that the attribute with the larger performance value earns a higher score. For example, if the value of the recycling rate (EN1) of a project is very high, its performance is good. Hence, the score rated by EN1 will be high.

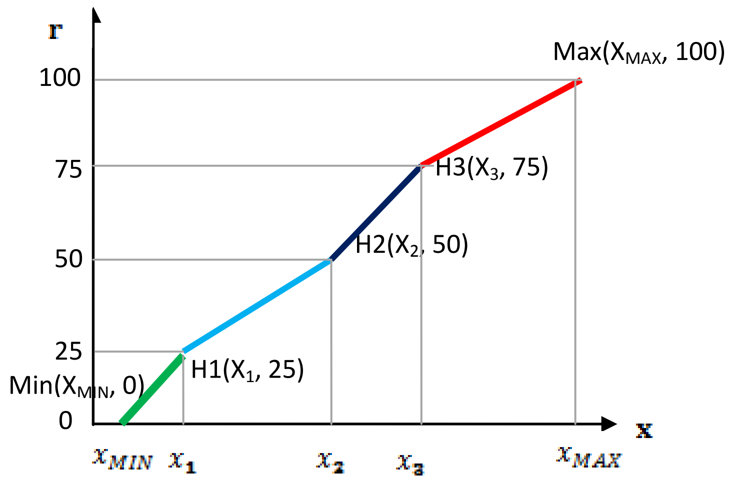


Figure 5.8 Rating functions (positive slope)

Following Equation 5.17, the rating function is given in Equation 5.21.

$$r_{ijk} = \mathrm{f(x)} = \begin{cases} 0, \ and x \in (0, \mathrm{x_{MIN}}) \\ 25 * \frac{\mathrm{x - x_{MIN}}}{\mathrm{x_1 - x_{MIN}}}, \ and x \in (\mathrm{x_{MIN}}, \mathrm{x_1}) \\ 25 + 25 * \frac{\mathrm{x - x_1}}{\mathrm{x_2 - x_1}}, \ and x \in (\mathrm{x_1}, \mathrm{x_2}) \\ 50 + 25 * \frac{\mathrm{x - x_2}}{\mathrm{x_3 - x_2}}, \ and x \in (\mathrm{x_2}, \mathrm{x_3}) \\ 75 + 25 * \frac{\mathrm{x - x_3}}{\mathrm{x_3 - x_{MAX}}}, \ and x \in (\mathrm{x_3}, \mathrm{x_{MAX}}) \\ 100, \ and x \in (\mathrm{x_{MAX}}, \infty) \end{cases} \quad \text{……… (Eq. 5.21)}$$

where r_{ijk} is the rating score given to the k th attribute under j th criteria, under i factor.

5.5.3.2 Method 2: Summated rating scales

Rating is based on a percentile score (0–100), decile score (0–10) or normalized score (0–1). For the score to correspond with those attributes rated using method 1, the percentile score (0-100) is adopted in this study. The performance of some attributes (such as EN4 and EC5.2) was measured based on a 5-point scale (where 1 is “extremely unsatisfactory”, 2 is “unsatisfactory”, 3 is “neutral”, 4 is “good” and 5 is “outstanding”). The rating scores corresponding to the performance scores are shown in Equation 5.22.

$$r_{ijk} = \begin{cases} 0, & x = \mathbf{1} \\ 25, & x = \mathbf{2} \\ 50, & x = \mathbf{3} \\ 75, & x = \mathbf{4} \\ 100, & x = \mathbf{5} \end{cases} \quad \text{………………………… (Eq. 5.22)}$$

5.5.4 MAVT- Aggregation method

The final step of MAVT is to aggregate the weights (Section 5.5.2) and the ratings (Section 5.5.3) to obtain a score. The score for each attribute was computed by multiplying the weight and the rating score. The additive method of aggregation was used to calculate the selection of structural material (SSM) score. The value function is given in Equation 5.23.

$$SSM_k = \omega_1 \sum_{j=1}^{5} \omega_{1j} r_{1j} + \omega_2 \sum_{j=1}^{4} \omega_{2j} r_{2j} + \omega_3 \sum_{j=1}^{4} \omega_{3j} r_{3j} \quad \text{. (Eq. 5.23)}$$

where SSM_k is the total score for structural material k. The option with a higher SSM score should be the one to be selected.

5.6 Method for validation

The validation exercise was conducted to verify whether the DSSSSM developed in this study could simulate the decision of an experienced management team as well as the reliability of defined weights, defined rating, and aggregate scores computed by this decision support system.

Two methods were used to validate the DSSSSM. One method involved investigating the consistency of the frames recommended by the DSSSSM and the options chosen for the real projects. The other method investigated whether the DSSSSM could simulate the real decision-making process of selection of structural frame. The DSSSSM is determined to be robust if the DSSSSM recommended the same frame as the real choice and experts confirmed that the DSSSSM could simulate the real decision process.

Experts who met the following criteria were selected:

- Have more than ten years working experience in the construction industry;

- Were deeply involved in the decision making on structural material selection of a real completed building project simultaneously proposed with both RC and SS frames; and

- Be able to provide accurate information about the estimation of performance of using two proposed frames. This information is required to complete the DSSSSM in Appendix 5.

Two experts were able to give information on projects ultimately constructed using the RC frame while the other two supplied information on projects constructed using the SS frame. These requirements ensured that the experts have in-depth knowledge and experience of structural material selection and would be able to provide the information requested by the DSSSSM.

In this study, four sets of new data provided by the four selected experts were input into the DSSSSM. If the frame recommended by the DSSSSM results is similar with the real choice, it can be concluded that the DSSSSM is robust. As all of the four projects had been completed, the decision on structural material had been made at least two years before the study. Therefore, the decision made by the project team in reality had no relevance with the DSSSSM.

5.7 Summary

The research design adopted in this research was the survey. The data collection instruments were four sets of structured questionnaires specially designed for this study. Data were collected through face to face interviews with designers, RC contractors, SS contractors, and demolition contractors.

Data analysis methods included t-test of means, Box-plots, Levene's test, unpaired t-test, and Kolmogorov-Smirnov test. T-test of the means was used to identify significantly important criteria and attributes. Box-plots method was used to describe the performance of the two structural frames. Levene's test, unpaired t-test, and Kolmogorov-Smirnov test were used to compare the performance differences of RC frames and SS frames in buildings. MAVT method was employed to construct the decision support system.

The validation exercise was conducted to investigate whether the structural frame material recommended by the DSSSSM developed in this study and the option chosen for the experts in real projects are the same. The validation was based on the information of four real projects provided by four experts who had been involved in the decision making of selection of structural frame.

CHAPTER 6 RESULTS AND DISCUSSION (OBJECTIVES 1 TO 3)

6.1 Introduction

This chapter analyses the data collected. The characteristics of the projects and respondents are described in Section 6.2. Section 6.3 examines the importance of the factors, criteria and attributes. Sections 6.4 to 6.6 address the first three research objectives (see Section 1.3). The results are discussed in Section 6.7.

6.2 Sample profiles

6.2.1 Profile of projects

Based on the sampling frame stated in Section 5.3.1, all BCA registered A1 and A2 building contractors were firstly contacted by telephone call and email. 74 of them were willing to participate in this survey by providing RC projects' information. Among the 188 builders with SS work license, only seven of them were willing to participate because they had constructed SS framed buildings before. It was found that more than 80% of the licensed SS builders had not constructed SS framed buildings. At the end of data collection period of 12 months, 26 incomplete questionnaires have been received. These were excluded from the study. Finally, complete data of 30 RC projects' and nine SS projects' data were obtained from 26 contractors and the seven SS builders, giving a response rate of 35% and 100% respectively. All of the respondents from builders are working for private companies.

The characteristics of the projects are shown in Table 6.1. The types of project included residential buildings (43.6%), commercial buildings (7.7%), office buildings and hotels (10.2%), institution buildings (12.8%), industrial buildings (7.7%) and mixed usage buildings (17.9%). The majority of the buildings are between 50m and 150 high. Among these projects, nine residential projects and five institutional projects were public projects. The rest of the 25 projects were developed by private sector. Of the 30 RC projects, 11 and 19 were public and private projects respectively. Among the 9 SS projects, 3 and 6 are public and private projects respectively.

Table 6.1 Profile of projects

Profile	Number			Percentage
Height				
≤ 50m	15			38.5%
51–100m	14			35.8%
101–150m	8			20.5%
151–200m	1			2.6%
> 200m	1			2.6%
Frame				
RC frame	30			76.9%
SS frame	9			23.1%
Project type	***RC***	***SS***	***Total***	
Residential	17	0	17	43.6%
Commercial	1	2	3	7.7%
Office/Hotel	2	2	4	10.2%
Institution	2	3	5	12.8%
Industrial	2	1	3	7.7%
Mixed	6	1	7	17.9%
Sector of the clients	***RC***	***SS***	***Total***	
Public	11	3	14	35.9%
Private	19	6	25	64.1%

The 30 RC projects were completed between 2009 and 2011, while the nine SS projects were completed between 2001 and 2011. The Construction time of projects are shown as below:

- 30 RC projects

  - Earliest date when project starts: 2006 Jun.
  - Latest date when project ends: 2011 Oct.
  - Min. duration of project: 12 months.
  - Max. duration of project: 60 months
  - Average project duration: 33.2 months

- 9 SS projects

- Earliest date when project starts: 1999 Mar.
- Latest date when project ends: 2011 Dec.
- Min. duration of project: 1 month
- Max. duration of project : 47 months
- Average project duration: 23 months

6.2.2 Profile of respondents

The information on the 30 RC framed buildings and nine SS framed buildings was obtained by interviewing 148 participants. These comprised 44 project managers or project directors working for main contractors, 17 experts working for SS contractors, 32 senior quantity surveyors, 36 senior engineers from design consultants, and 19 experts working for clients. The average number of years of the interviewees' working experience was 12 years while the lowest number of years of working experience was five years. Among the 148 respondents, 24 and 124 were from public and private sectors. Of the 24 from public sector, 83.3% and 16.7% are senior management and middle management respectively. Among the 124 from private sector, 77.4% and 22.6% are senior management and middle management respectively. All of the respondents from builders are working for private companies.

The respondents for steel and concrete are different. The performances of RC buildings were obtained from RC contractors and the performances of RC buildings were obtained from SS builders.

6.3 Importance of factors, criteria and attributes

The respondents were asked to rate the level of importance of the factors, criteria and attributes shown in Figure 5.3 on a 5-point Likert scale. These were subject to t-test of the mean, to ascertain if they are significantly important.

6.3.1 T- test on importance of factors

In order to test Hypothesis 1 (decision making on structural material selection is integrally affected by the material's performance in economic sustainability, environmental sustainability, and constructability), the respondents were asked to provide their views on whether the three factors are important for their decisions on selection of structural materials. In the questionnaire, 1 means “extremely not important”, 2 means “not important”, 3 means “neutral”, 4 means “important” and 5 means “very important”.

After the 39 sets of data of respondents’ preference were input into SPSS, one sample t test was conducted. Table 6.2 reported the t-test results of respondents’ views on the importance of the three factors. It is shown that all of the means of the three factors were larger than 3, while all of the significance values (2-tailed) were less than 0.05 with 95% confidence interval. Therefore, it is concluded that the three factors (EC, EN, CP) are important for decision making on structural material selection.

Table 6.2 T- test on importance of factors

Factor	Mean	Test Value = 3		
		t	Sig. (2-tailed)	Mean Difference
Economic sustainability (EC)	4.85	31.54	0.000	1.85
Environmental sustainability (EN)	3.33	3.14	0.003	0.33
Constructability performance (CP)	4.82	25.19	0.000	1.82

6.3.2 T- test on importance of criteria and attributes

The respondents were asked to rank the importance of each attribute when a decision is to be made on the type of structural material. The 39 sets of data collected were then input into SPSS to conduct sample t-tests (see section 5.4.1). According to the results of significance (2-tailed) value and mean difference, those attributes were regarded as not important when the significance value was less than 0.05 with a negative *t* value. Those non-important attributes were not included in the decision support system.

Table 6.3 shows the t-test results of the mean and importance of each attribute. Six attributes that did not pass the t-test (significance value ≤ 0.05 and negative *t* value) are:

EC3.2: Corporate taxes

EC4: End of life costs

EC5.3: Possible incentives from the government

EN1.2: The reuse rate of structural materials

EN1.4: The reusability of structural materials

EN2: CO_2 emission

Table 6.3 T-test of importance of criteria and attributes

Criteria/ attibutes	Mean	Std. Deviation	Test Value = 3				
			t	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
						Lower	Upper
EC1	4.385	0.633	13.658	0.000	1.385	1.179	1.590
EC2	3.308	0.731	2.629	0.012	0.308	0.071	0.545
EC3	3.308	1.127	1.704	0.097	0.308	-0.058	0.673
EC3.1	3.333	1.060	1.965	0.057	0.333	-0.010	0.677
EC3.2	1.718	0.759	-10.547	0.000	-1.282	-1.528	-1.036
EC4	2.436	1.046	-3.367	0.002	-0.564	-0.903	-0.225
EC5	3.000	0.725	0.000	1.000	0.000	-0.235	0.235
EC5.1	3.256	0.751	2.132	0.040	0.256	0.013	0.500
EC5.2	3.103	0.852	0.752	0.457	0.103	-0.174	0.379
EC5.3	2.359	0.986	-4.058	0.000	-0.641	-0.961	-0.321
EN1	3.179	1.023	1.096	0.280	0.179	-0.152	0.511
EN1.1	3.128	0.978	0.819	0.418	0.128	-0.189	0.445

Criteria/ attibutes	Mean	Std. Deviation	Test Value = 3				
			t	Sig. (2-tailed)	Mean Difference	95% Confidence Interval of the Difference	
						Lower	Upper
EN1.2	2.282	1.099	-4.080	0.000	-0.718	-1.074	-0.362
EN1.3	2.718	0.972	-1.812	0.078	-0.282	-0.597	0.033
EN1.4	2.026	1.246	-4.884	0.000	-0.974	-1.378	-0.571
EN1.5	2.795	1.151	-1.113	0.273	-0.205	-0.578	0.168
EN2	2.308	0.694	-6.229	0.000	-0.692	-0.917	-0.467
EN3	2.846	0.779	-1.233	0.225	-0.154	-0.406	0.099
EN4	3.462	1.315	2.192	0.035	0.462	0.035	0.888
CP1	3.949	0.999	5.933	0.000	0.949	0.625	1.272
CP2	4.513	0.683	13.826	0.000	1.513	1.291	1.734
CP3	4.205	0.978	7.694	0.000	1.205	0.888	1.522
CP4	4.333	0.772	10.781	0.000	1.333	1.083	1.584

Except EN2 (CO_2 emission), the other five non-important criteria were removed from the framework. Therefore, the performance of EC3.2, EC5.3, EN1.2, and EN1.4 are not analyzed in the following section. The performance of EC4 is not investigated and Questionnaire 4 is not conducted.

Although the sample mean is differ from population mean, the law of large numbers dictates that the larger the size of the sample, the more likely it is that the sample mean will be close to the population mean (Underhill& Bradfield, 1998. Mean and the standard deviation of a set of data are widely used for descriptive statistics in many area, such as particle physics (Banis, 2011), finance (Incandela, 2012), and project management (Utama& Gheewala, 2009). Therefore, it is valid for this study to use means and standard deviation for statistical analysis.

6.4 Economic Sustainability Performance of RC and SS

6.4.1 Structural costs (EC1)

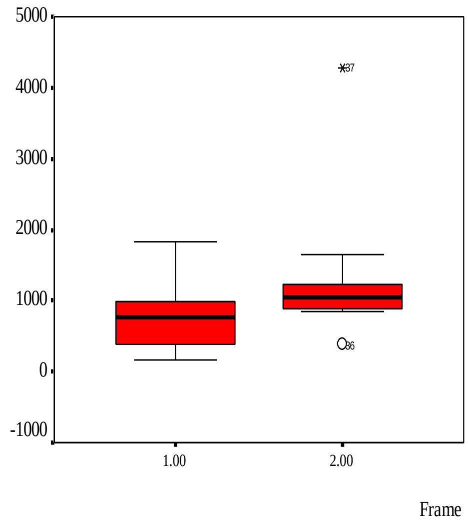
- Description

This study analyzed the structural costs of buildings. Participants were asked to provide the final structural costs of their projects. In most instances, participants did not know the costs of whole project. In order to eliminate the influence of project size on structural costs, the structural cost is converted to unit structural cost (S$/m^2) using the following formula:

Unit structural cost (S$/m^2) = Total structural cost / Total GFA... *(Eq. 6.1)*

Table 6.4 reports the descriptive statistics for structural costs. The structural costs of the 30 RC framed projects range from S$166.70/m^2 to S$1,823.60/m^2 with a median value of S$758.60/m^2, while that of the nine SS framed projects range from S$375.00/ m^2 to S$4,285.70/m^2 with a median value of S$1,055.80/m^2.

Table 6.4 Statistical description (EC1)

Frame	**Descriptive**		**Boxplot**
1. RC	Number	30	
	Median	758.60	
	Mean	727.12	
	Std. Deviation	386.76	
2. SS	Number	9	
	Median	1055.80	
	Mean	1388.07	
	Std. Deviation	1137.81	

- Distribution test on SS group

The Kolmogorov-Smirnov test was conducted to test if the distribution of the group of SS framed projects is normal. Table 6.5 shows that the asymptotic significance is 0.94 (p> 0.05), which indicates the distribution of this group is normal. Levene's test was therefore the appropriate test for comparing the difference in EC1 between the RC group and the SS group.

Table 6.5 One-sample Kolmogorov-Smirnov Test (EC1)

Frame	Kolmogorov-Smirnov Test		EC1
SS	N		9
	Normal Parameters	Mean	1,025.86
		Std. Deviation	337.47
	Kolmogorov-Smirnov Z		0.53
	Asymp. Sig. (2-tailed)		0.94
Distribution is normal.			

- Comparative result

The t-test of equality of means in Table 6.6 shows that the difference in structural cost (EC1) between RC and SS is significant (sig= 0.04). As the mean difference is negative, it is concluded that the structural costs of SS framed buildings are significantly higher than RC framed buildings.

Table 6.6 Levene's test and t-test for equality (EC1)

EC1	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	1.40	0.25	-2.09	37	0.04	-298.75
Equal variances not assumed			-2.25	14.91	0.04	-298.75

6.4.2 Maintenance costs (EC2)

- Description

Interviewees were asked to provide information on the maintenance method and maintenance costs of their projects so that maintenance costs could be examined. Interviewees shared that RC framed buildings do not typically require maintenance once the project is completed, while SS frames buildings do. When the life expectancies of the fireproofing system and anti-corrosion system of SS elements are added, a test should be done to examine whether the two systems still achieve the standards for fireproofing and anti-corrosion. The maintenance of SS frames is actually reconstruction of fireproofing system and anti-corrosion system when the life expectancies of the two systems end and the test is failed. There will not be additional maintenance for SS elements during the life span. Therefore, the maintenance costs were measured by the costs of new construction of fireproofing system and anti-corrosion system.

Because the fireproofing system and anti-corrosion system were combined together, the respondents provided the total costs of fireproofing system and anti-corrosion system instead of providing the two costs separately. In addition, the respondents did not have sufficient knowledge of the material used for fireproofing and anti-corrosion system because these works were not conducted by SS contractors. As the materials were outside the scope, this study did not trace to the subcontractors for the fireproofing and anti-corrosion material information. Therefore, only the total costs of fireproofing system and anti-corrosion system (maintenance cost) were analyzed by this study.

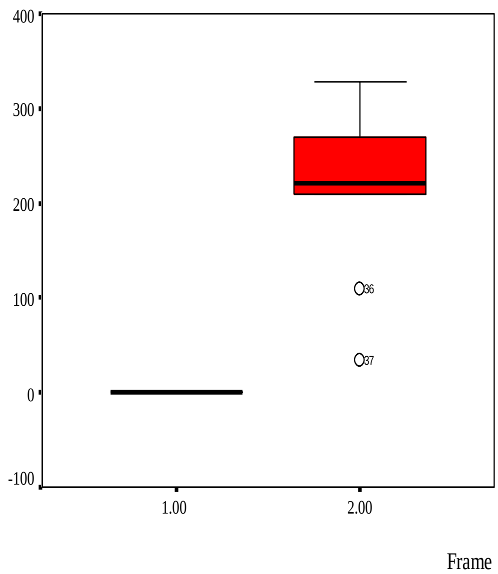
From the investigation on the life expectancy of the fireproofing system and anti-corrosion system, among the nine SS projects, two have a life expectancy of 30 years, five have a life expectancy of 15 years, and two have a life expectancy of 10 years. It was assumed all buildings have life expectancy of 50 years. Then the total life cycle cost for maintenance was calculated over 50 years. Taking a fireproofing system with a life expectancy of 15 years an example, the life cycle maintenance cost is three multiplies the costs of fireproofing works for each time because it will need three times maintenance over 50 years.

In order to eliminate the influence of project size on maintenance costs, the maintenance cost was converted to unit maintenance cost (S$/$m^2$) using the following formula:

Unit maintenance cost (S$/*$m^2$) = Total maintenance cost / Total GFA ..(Eq. 6.2)*

Table 6.7 reports the descriptive statistics for maintenance costs. As explained above, maintenance cost of the RC framed projects is $0, while that of the nine SS framed projects range from S$34.60/$m^2$ to S$328.10/$m^2$ with a median value of S$221.70/$m^2$.

Table 6.7 Statistical description (EC2)

Frame	Descriptive (EC2)		Boxplot
1. RC	Number	30	
	Median	0	
	Mean	0	
	Std. Deviation	0	
2. SS	Number	9	
	Median	221.70	
	Mean	216.49	
	Std. Deviation	93.62	

- Distribution test on SS group

Table 6.8 shows that the asymptotic significance is 0.94 ($p > 0.05$), which indicates that the distribution of EC2 data for SS framed projects is normal. Levene's test is therefore the appropriate test for comparing the difference in EC2 between the RC group and the SS group.

Table 6.8 One-sample Kolmogorov-Smirnov Test (EC2)

Frame	Kolmogorov-Smirnov Test		EC2
SS	N		9
	Normal Parameters	Mean	216.49
		Std. Deviation	93.62
	Kolmogorov-Smirnov Z		0.53
	Asymp. Sig. (2-tailed)		0.94
Distribution is normal.			

- Comparative result

Table 6.9 shows that the difference in EC2 between RC and SS is significant (sig= 0.00). As the mean difference is negative, it is concluded that the maintenance costs of SS framed buildings are significantly higher than RC framed buildings.

Table 6.9 Levene's test and t-test for equality (EC2)

EC2	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	37.32	0.00	-13.09	37	0.00	-216.49
Equal variances not assumed			-6.94	8.00	0.00	-216.49

6.4.3 Non-construction costs (EC3)

- Description

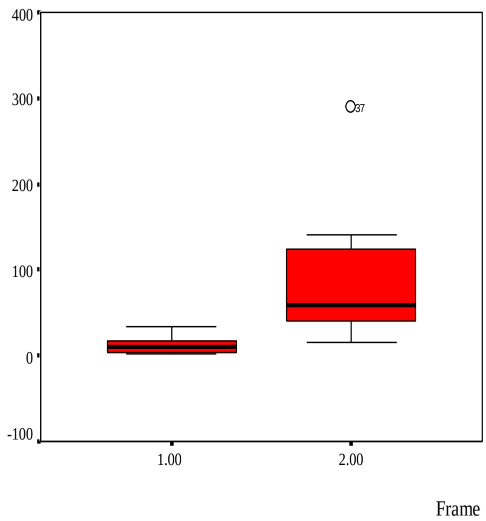
Non-construction costs (EC3) comprised financial costs and taxes. The tax component (EC3.2) was removed from the DSSSSMbecause it is a non-important attribute (see section 6.3.2), leaving only financial costs (EC3.1) includes only the additional financial costs that would be incurred should the frame material be changed. EC3.1 is calculated using Eq. 6.3.

EC3.1 (S$/*m^2) = Proportion of loan * Unit structural cost*

** Average loan period * Loan rate   ………(Eq. 6.3)*

Table 6.10 reports the descriptive statistics for financial costs. The financial costs of the 30 RC framed projects range from S$1.69/m^2 to S$33.74/m^2 with a median value of S$10.79/ m^2, while that of the nine SS framed projects range from S$ 14.74/ m^2 to S$274.55/ m^2 with a median value of S$59.06/ m^2.

Table 6.10 Statistical description (EC3.1)

Frame	**Descriptive (EC3.1)**		**Boxplot**
1. RC	Number	30	
	Median	10.79	
	Mean	12.42	
	Std. Deviation	9.23	
2. SS	Number	9	
	Median	59.06	
	Mean	94.90	
	Std. Deviation	84.78	

- Distribution test on SS group

Table 6.11 shows that the asymptotic significance is 0.94 ($p > 0.05$), which indicates that the distribution of this group of SS data is normal. Levene's test is therefore the appropriate test for comparing the difference in EC3.1 between the RC group and the SS group.

Table 6.11 One-sample Kolmogorov-Smirnov Test (EC3.1)

Frame	Kolmogorov-Smirnov Test		EC3.1
SS	N		9
	Normal Parameters	Mean	94.90
		Std. Deviation	84.74
	Kolmogorov-Smirnov Z		0.53
	Asymp. Sig. (2-tailed)		0.94
Distribution is normal.			

- Comparative result

Table 6.12 shows that the difference in EC3.1 between RC and SS is significant (sig= 0.02). As the mean difference is negative, it is concluded that the financial costs of SS framed buildings are significantly higher than RC-framed buildings.

Table 6.12 Levene's test and t-test for equality (EC3.1)

EC3.1	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	32.07	0.00	-5.39	37.00	0.00	-82.48
Equal variances not assumed			-2.92	8.06	0.02	-82.48

6.4.4 Additional income (EC5)

6.4.4.1 <u>Additional usable area (EC5.1)</u>

- Description

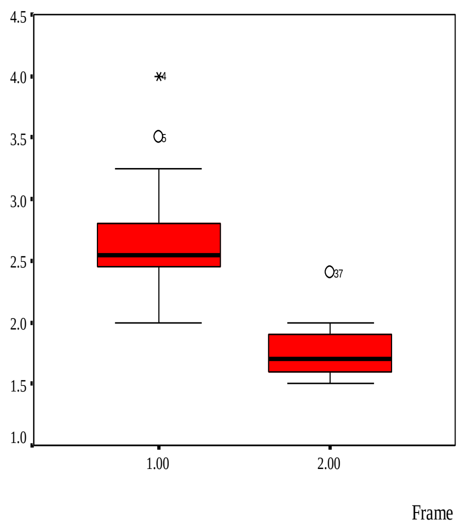
Compared to RC framed buildings, additional floor area is made available in SS framed buildings because they have smaller or more slender columns. The proportion of sectional area of columns over the GFA of a standard level (%) is therefore used to describe EC5.1.

*EC5.1 (%) = Sectional area of columns / GFA of a standard level *100%.*

.....(Eq. 6.4)

Table 6.13 reports the descriptive statistics for Additional usable area. The proportion of area occupied by the columns of the 30 RC framed projects ranges from 2.00% to 4.00% with a median value of 2.55%, while that of the nine SS framed projects ranges from 1.50% to 2.00% with a median value of 1.78%.

Table 6.13 Statistical description (EC5.1)

Frame	**Descriptive (EC5.1)**		**Boxplot**
1. RC	Number	30	
	Median	2.55%	
	Mean	2.68%	
	Std. Deviation	0.43	
2. SS	Number	9	
	Median	1.70%	
	Mean	1.78%	
	Std. Deviation	0.29	

- Distribution test on SS group

Table 6.14 shows that the asymptotic significance is 0.96 ($p > 0.05$), which suggests the distribution of this group of SS data is normal. Levene's test is therefore the appropriate test for comparing the difference in EC5.1 between the RC group and the SS group.

Table 6.14 One-sample Kolmogorov-Smirnov Test (EC5.1)

Frame	Kolmogorov-Smirnov Test		EC5.1
SS	N		9
	Normal Parameters	Mean	1,025.86
		Std. Deviation	337.47
	Kolmogorov-Smirnov Z		0.51
	Asymp. Sig. (2-tailed)		0.96
Distribution is normal.			

- Comparative result

Table 6.15 shows that the difference in EC5.1 between RC and SS is significant (sig= 0.00). As the mean difference is positive, it is concluded that sectional area of columns of SS framed buildings is significantly smaller than RC framed buildings. Therefore, the Additional usable area of SS framed buildings is larger than RC framed buildings.

Table 6.15 Levene's test and t-test for equality (EC5.1)

EC5.1	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	1.01	0.32	5.87	37	0.00	0.89
Equal variances not assumed			7.22	19.75	0.00	0.89

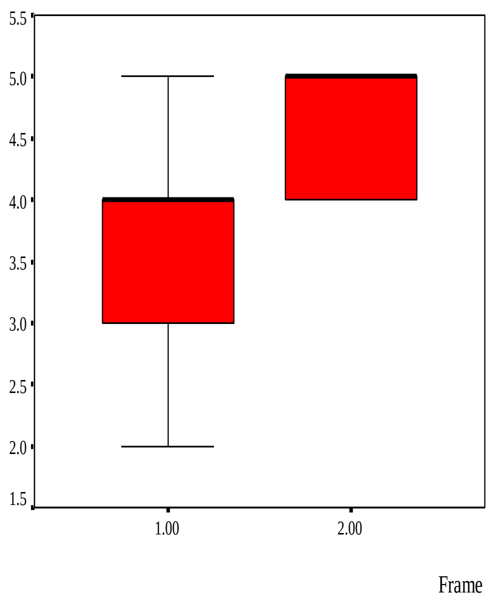
6.4.4.2 Flexibility (EC5.2)

- Description

Flexibility was measured based on a 5-point Likert scale (1 is "unsatisfactory", 2 is "satisfactory", 3 is "neutral", 4 is "good" and 5 is "outstanding").

Table 6.16 reports the descriptive statistics for flexibility. The flexibility of the 30 RC framed projects ranges from 2 to 5 with a median value of 4, while that of the nine SS framed projects ranges from 4 to 5 with a median value of 5.

Table 6.16 Statistical description (EC5.2)

Frame	**Descriptive (EC5.2)**		**Boxplot**
1. RC	Number	30	
	Median	4	
	Mean	3.79	
	Std. Deviation	0.82	
2. SS	Number	9	
	Median	5	
	Mean	4.56	
	Std. Deviation	0.53	

- Distribution test on SS group

Table 6.17 shows that the asymptotic significance is 0.20 ($p > 0.05$), which indicates that the distribution of this group of SS data is normal. Levene's test is therefore the appropriate test for comparing the difference in EC5.2 between the RC group and the SS group.

Table 6.17 One-sample Kolmogorov-Smirnov Test (EC5.2)

Frame	Kolmogorov-Smirnov Test		EC5.2
SS	N		9
	Normal Parameters	Mean	1,025.86
		Std. Deviation	337.47
	Kolmogorov-Smirnov Z		1.07
	Asymp. Sig. (2-tailed)		0.20
Distribution is normal.			

- Comparative result

Table 6.18 shows that the difference in EC5.2 between RC and SS is significant (sig= 0.01). As the mean difference is negative, it is concluded that the flexibility of SS framed buildings is significantly better than RC framed buildings.

Table 6.18 Levene's test and t-test for equality (EC5.2)

EC5.2	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	1.61	0.21	-2.72	37	0.01	-0.79
Equal variances not assumed			-3.42	20.73	0.00	-0.79

6.5 Environmental Sustainability Performance of RC and SS

6.5.1 Material consumption (EN1)

In the conceptual framework, there are five attributes (EN1.1-EN1.5) under criteria EN1. In this section, EN1.2 and EN1.4 are not analyzed because they were tested as non-important attributes (see Table 6.3) and have been removed from the DSSSSM.

6.5.1.1 Recycling rate (EN1.1)

- Measurement and description

The recycling rate (EN1.1) refers to the percentage of recycled material used against total material consumption. It should be noted that the 'recycling rate' in this study has different meaning from the 'recycling rate' given by NEA website. The 'recycling rate' used by NEA means the proportion of a typical recycled waste material against total of the waste in each year.

For SS projects, steel is the main material used to construct the structural frame. The recycling rate is obtained by summing up the recycling rate in the steel manufacturing stage and the recycling rate in the construction stage.

$$EN1.1\ (\%) = rr_{CS} + (1 - rr_{CS}) * rr_{MS} \quad \text{....................}(Eq.\ 6.5)$$

where rr_{MS} is the percentage of steel scrap being used as raw material in the steel manufacturing stage; rr_{CS} is the percentage of recycled steel being used for prefabrication in the construction stage.

According to Section 3.2.2, steel production occurs at an integrated facility from iron ore or at a secondary facility, which produce steel mainly from recycled steel scrap. In 2011, 37.7% of steel was made of steel scrap in the world wide is (BIR, 2012). As almost all of the steel used in Singapore construction industry is imported, 37.7% is set as the recycling rate of steel in the manufacturing stage ($rr_{MS} = 37.7\%$).

For RC projects, the two main materials used to construct the structural frame are concrete and steel. In order to compute a single recycling rate which combines the recycling rates of both concrete and steel, the measurement of the two materials should be based on a similar denominator, such as cost, volume or weight. Normally, price reflects value (Vianello, 1989). Hence, the monetary dimension would seem to be the most reasonable choice as the common denominator here as it is integrally involved in both materials.

According to the investigation, the unit ton is widely used to describe the amount of steel consumption while m^3 is used to describe the amount of concrete consumption.

Equation 6.6 shows the formula for calculating the recycling rate of RC projects

$$EN1.1(\%) = \frac{(SC * steel\ price) * (rr_{CS} + (1 - rr_{CS}) * rr_{MS}) + (CC * concrete\ price) * (rr_{MC} + rr_{CC})}{SC * \ steel\ price + \ CC \ * concrete\ price}$$

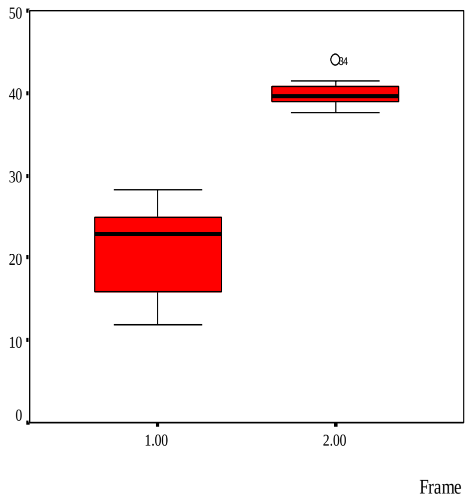
$$= \frac{(SC * steel\ price) * rr_{MS}}{SC * \ steel\ price + CC * concrete\ price} \qquad \text{......(Eq.6.6)}$$

where SC is the amount of steel consumption; CC is the amount of concrete consumption. rr_{MC} and rr_{CC} are the percentages of using recycled concrete as raw material in the concrete manufacturing stage and the construction stage respectively. As using recycled concrete to produce any structural element is not allowed in Singapore, $rr_{MC} = 0,\ rr_{CC} = 0$.

The annual steel price and the annual concrete price provided by BCA (2011) are used in Equation 6.6.

Table 6.19 reports the descriptive statistics for EN1.1. The recycling rate of the 30 RC framed projects ranges from 11.83% to 28.30% with a median value of 22.93%, while that of the nine SS framed projects ranges from 37.7% to 43.93% with a median value of 39.57%.

Table 6.19 Statistical description (EN1.1)

Frame	Descriptive (EN1.1)		Boxplot
1. RC	Number	30	
	Median	22.93%	
	Mean	21.21%	
	Std. Deviation	0.05	
2. SS	Number	9	
	Median	39.57%	
	Mean	40.12%	
	Std. Deviation	0.02	

- Distribution test on SS group

Table 6.20 shows that the asymptotic significance is 0.94 ($p > 0.05$), which suggests that the distribution of this group of SS data is normal. Levene's test is therefore the appropriate test for comparing the difference in EN1.1 between the RC group and the SS group.

Table 6.20 One-sample Kolmogorov-Smirnov Test (EN1.1)

Frame	Kolmogorov-Smirnov Test		EN1.1
SS	N		9
	Normal Parameters	Mean	40.12%
		Std. Deviation	0.02
	Kolmogorov-Smirnov Z		0.53
	Asymp. Sig. (2-tailed)		0.94
Distribution is normal.			

- Comparative result

Table 6.21 shows that the difference in EN1.1 between RC and SS is significant (sig= 0.00). As the mean difference is negative, it is concluded that the recycling rate of the RC group is lower than the SS group, which implies that the performance of EN1.1 of SS framed buildings is significantly better than RC framed buildings.

Table 6.21 Levene's test and t-test for equality (EN1.1)

EN1.1	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	Df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	11.63	0.00	-10.43	37	0.00	-18.91
Equal variances not assumed			-16.59	36.18	0.00	-18.91

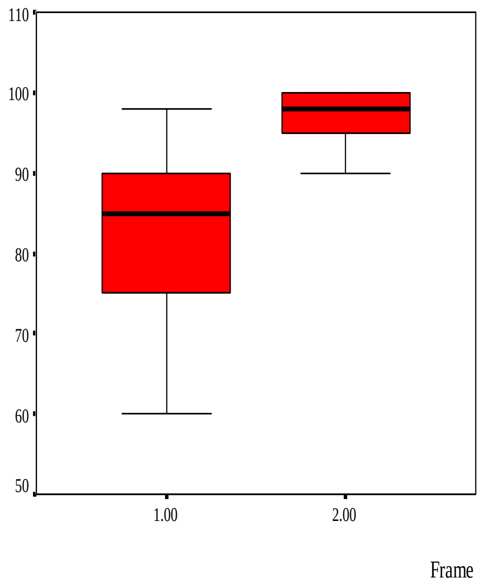
6.5.1.2 Recyclability (EN1.3)

- Description

Recyclability is measured by the proportion of recyclable structural material in the end of life stage. It is different from recycling rate, which focuses on the manufacturing stage and the construction stage. For example, Concrete can be recycled and be used up to 20% replacement of naturally source aggregates for structural concrete. Recycled concrete can also be used for other uses such as concrete pad.

Table 6.22 reports the descriptive statistics for EN1.3. The recyclability rate of the 30 RC framed projects ranges from 60% to 98% with a median value of 85%, while that of the nine SS framed projects ranges from 90% to 100% with a median value of 98%.

Table 6.22 Statistical description (EN1.3)

Frame	**Descriptive (EN1.3)**		**Boxplot**
1. RC	Number	30	
	Median	85%	
	Mean	83%	
	Std. Deviation	0.08	
2. SS	Number	9	
	Median	98%	
	Mean	97%	
	Std. Deviation	0.04	

- Distribution test on SS group

Table 6.23 shows that the asymptotic significance is 0.62 ($p > 0.05$), which suggests that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in EN1.3 between the RC group and the SS group.

Table 6.23 One-sample Kolmogorov-Smirnov Test (EN1.3)

Frame	Kolmogorov-Smirnov Test		EN1.3
SS	N		9
	Normal Parameters	Mean	0.97
		Std. Deviation	0.04
	Kolmogorov-Smirnov Z		0.76
	Asymp. Sig. (2-tailed)		0.62
Distribution is normal.			

- Comparative result

Table 6.24 shows that the difference in EN1.3 between RC and SS is significant (sig= 0.00). As the mean difference is negative, it is concluded that the recyclability rate of the RC group is less than the SS group, which implies that the performance of EN1.3 of SS framed buildings is significantly better than RC framed buildings.

Table 6.24 Levene's test and t-test for equality (EN1.3)

EN1.3	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	4.12	0.05	-4.86	37	0.00	-13.98%
Equal variances not assumed			-7.14	31.02	0.00	-13.98%

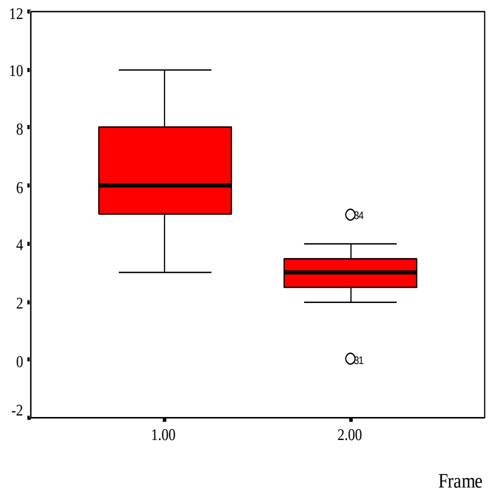
6.5.1.3 Waste Rate (EN1.5)

- Description

Waste rate is measured by the percentage of wasted material against total material consumption.

Table 6.25 reports the descriptive statistics for EN1.5. The waste rate of the 30 RC framed projects ranges from 3% to 10% with a median value of 6%, while that of the nine SS framed projects ranges from 0 to 5% with a median value of 3%.

Table 6.25 Statistical description (EN1.5)

Frame	**Descriptive (EN1.5)**		**Boxplot**
1. RC	Number	30	
	Median	6%	
	Mean	6%	
	Std. Deviation	0.02	
2. SS	Number	9	
	Median	3%	
	Mean	3%	
	Std. Deviation	0.01	

- Distribution test on SS group

Table 6.26 shows that the asymptotic significance is 0.870 (p > 0.05), which suggests that the distribution of this group of data is normal. Levene’s test is therefore the appropriate test for comparing the difference in EN1.5 between the RC group and the SS group.

Table 6.26 One-sample Kolmogorov-Smirnov Test (EN1.5)

Frame	Kolmogorov-Smirnov Test		EN1.5
SS	N		9
	Normal Parameters	Mean	3%
		Std. Deviation	1.39
	Kolmogorov-Smirnov Z		0.60
	Asymp. Sig. (2-tailed)		0.87
Distribution is normal.			

- Comparative result

Table 6.27 shows that the difference in EN1.5 between RC and SS is significant (sig= 0.00). As the mean difference is positive, it is concluded that the waste rate of the RC group is higher than the SS group, which implies that the performance of EN1.3 of SS framed buildings is significantly better than RC framed buildings.

Table 6.27 Levene's test and t-test for equality (EN1.5)

EN1.5	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	4.48	0.04	4.79	37	0.00	3.38
Equal variances not assumed			5.78	18.73	0.00	3.38

6.5.2 *CO_2 emission during construction (EN2)*

- Description

CO_2 emission at a construction site is produced by the consumption of electricity, diesel and gasoline. In order to minimize the influence of project size on CO_2 emission, EN2 is measured by unit CO_2 emission (kg/m^2). The performance value of EN2 is computed by Equations 6.7 to 6.11

$$EN2\ (\text{kg/m}^2) = \text{Total } CO_2 \text{ emission / Total GFA} \quad \ldots\ldots\ldots\ldots\ldots (Eq.\ 6.7)$$

$$\text{Total } CO_2 \text{ emission (kg)} = E_E + E_D + E_G \ldots\ldots\ldots\ldots\ldots (Eq.\ 6.8)$$

where E_E is the CO_2 emission produced by electricity consumption;

E_D is the CO_2 emission produced by diesel consumption;

E_G is the CO_2 emission produced by gasoline consumption.

As shown in Equations 6.9 to 6.11, the amount of CO_2 emission produced by each energy source is calculated by multiplying the amount of energy consumption and the corresponding emission factor provided by US EPA (2011).

E_E (kg) = 0.5206 (kg/kwh) * Electricity consumption from power grid (kwh)

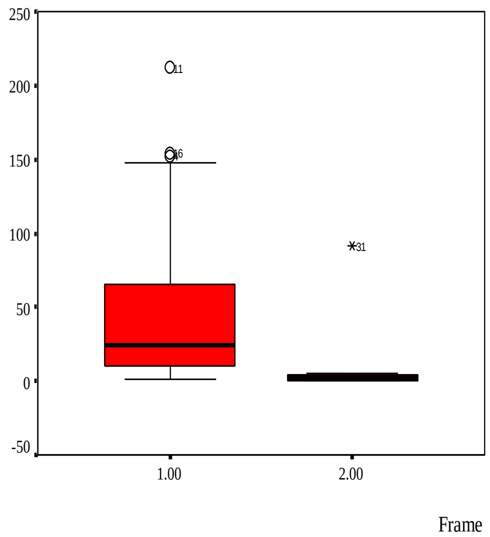
……. .*(Eq. 6.9)*

E_D (kg) = 2.6972 (kg/l)* diesel consumption (l) ………..……..*(Eq. 6.10)*

E_D (kg) =2.1953 (kg/l)* gasoline consumption (l) …………………*(Eq. 6.11)*

Table 6.28 reports the descriptive statistics for EN2. The CO_2 emission during construction stage produced by the 30 RC framed projects ranges from 0.80 kg/m^2 to 211.80 kg/m^2 with a median value of 24.40 kg/m^2 while that of the nine SS framed projects ranges from 0.10 kg/m^2 to 91.00 kg/m^2 with a median value of 11.69 kg/m^2.

Table 6.28 Statistical description (EN2)

Frame	**Descriptive (EN2)**		**Boxplot**
1. RC	Number	30	
	Median	24.40	
	Mean	51.80	
	Std. Deviation	58.87	
2. SS	Number	9	
	Median	1.70	
	Mean	11.69	
	Std. Deviation	29.80	

- Distribution test on SS group

Table 6.29 shows that the asymptotic significance is 0.03 ($p < 0.05$), which means the distribution of this group is not normal. Levene's test is therefore not the appropriate test for comparing the difference in EN2 between the RC group and the SS group (refer to Figure 5.1). The two-sample Kolmogorov-Smirnov test was then used to test the difference.

Table 6.29 One-sample Kolmogorov-Smirnov Test (EN2)

Frame	Kolmogorov-Smirnov Test		EN2
SS	N		9.000
	Normal Parameters(a,b)	Mean	11.69
		Std. Deviation	29.80
	Kolmogorov-Smirnov Z		1.43
	Asymp. Sig. (2-tailed)		0.03
Distribution is not normal.			

- Comparative result

Table 6.30 shows that the difference in EN2 between RC and SS is significant (sig: 0.00). As the mean difference is positive, it is concluded that the CO_2 emission of the RC group is higher than the SS group, which implies that the performance of EN2 of SS buildings is significantly better than RC framed buildings.

Table 6.30 Two-sample Kolmogorov-Smirnov Test

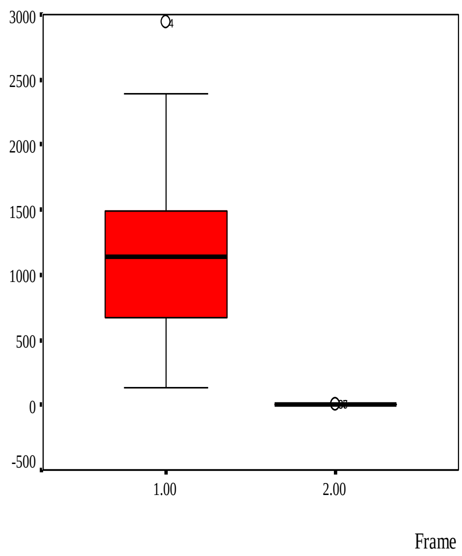
Two-Sample Kolmogorov-Smirnov Test		EN2
Most Extreme Differences	Absolute	0.76
	Positive	0.00
	Negative	-0.76
Kolmogorov-Smirnov Z		1.99
Asymp. Sig. (2-tailed)		0.00

6.5.3 *Water consumption (EN3)*

- Description

Data on water consumption (EN3), measured by unit water consumption (l/m^2), is shown in Table 6.31. The unit water consumption of the 30 RC framed projects ranges from 133.20 l/m^2 to 11,099.30 l/m^2 with a median value of 1,143.25 l/m^2, while that of the nine SS framed projects ranges from 0 to 7.10 l/m^2 with a median value of 0.20 l/m^2.

Table 6.31 Statistical description (EN3)

Frame	Descriptive (EN3)		Boxplot
1. RC	Number	30	
	Median	1143.25	
	Mean	1467.97	
	Std. Deviation	1922.28	
2. SS	Number	9	
	Median	0.20	
	Mean	1.89	
	Std. Deviation	2.82	

- Distribution test on SS group

Table 6.32 shows that the asymptotic significance is 0.33 ($p > 0.05$), which indicates that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in EN3 between the RC group and the SS group.

Table 6.32 One-sample Kolmogorov-Smirnov Test (EN3)

Frame	Kolmogorov-Smirnov Test		EN3
SS	N		9
	Normal Parameters	Mean	1.89
		Std. Deviation	2.82
	Kolmogorov-Smirnov Z		0.95
	Asymp. Sig. (2-tailed)		0.33
Test distribution is normal.			

- Comparative result

Table 6.33 shows that the difference in EN3 between RC and SS is significant (sig: 0.03). As the mean difference is positive, it is concluded that water consumption of the RC group is higher than the SS group, which implies that the performance of EN3 of SS framed buildings is significantly better than RC framed buildings.

Table 6.33 Levene's test and t-test for equality (EN3)

EN3	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	2.28	0.14	2.27	37	0.03	1,466.08
Equal variances not assumed			4.18	29.00	0.00	1,466.08

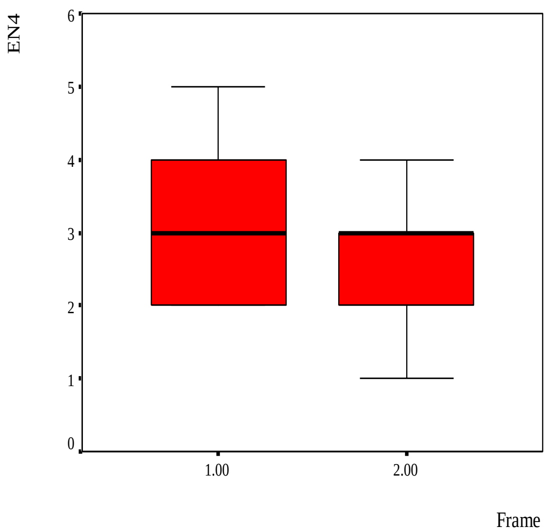
6.5.4 Noise (EN4)

- Description

Noise is measured based on a 5-point Likert scale (1 is "extremely unsatisfactory", 2 is "unsatisfactory", 3 = "neutral", 4 is "good", 5 is "outstanding").

Table 6.34 reports the descriptive statistics for noise. The rating of noise for the 30 RC framed projects ranges from 2 to 5 with a median value of 3, while that of the nine SS framed projects ranges from 1 to 4 with a median value of 3.

Table 6.34 Statistical description (EN4)

Frame	**Descriptive (EN4)**		**Boxplot**
1. RC	Number	30	
	Median	3	
	Mean	3.10	
	Std. Deviation	0.85	
2. SS	Number	9	
	Median	3	
	Mean	2.56	
	Std. Deviation	0.88	

- Distribution test on SS group

Table 6.35 shows that the asymptotic significance is 0.33 ($p > 0.05$), which indicates that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in EN4 between the RC group and the SS group.

Table 6.35 One-sample Kolmogorov-Smirnov Test (EN4)

Frame	Kolmogorov-Smirnov Test		EN4
SS	N		9
	Normal Parameters	Mean	2.56
		Std. Deviation	0.88
	Kolmogorov-Smirnov Z		0.95
	Asymp. Sig. (2-tailed)		0.33
Distribution is normal.			

- Comparative result

Table 6.36 shows that the difference in EN4 between RC and SS is not significant as the significance value is 0.10, which is higher than 0.05. It is concluded that the noise impact produced by SS framed buildings is not significantly different from RC framed buildings.

Table 6.36 Levene's test and t-test for equality (EN4)

EN4	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	0.07	0.79	1.68	37	0.10	0.54
Equal variances not assumed			1.64	12.75	0.13	0.54

6.6 Constructability Performance of RC and SS

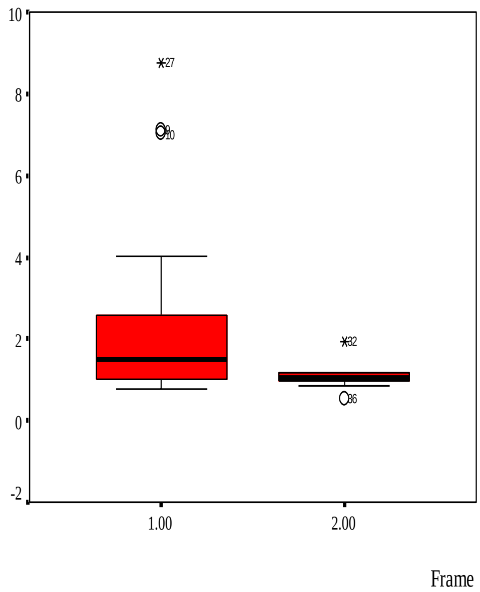
6.6.1 Labor consumption (CP1)

- Description

Labor consumption is measured by the unit labor consumption (manday/m^2).

Table 6.37 reports the descriptive statistics for CP1. The unit labor consumption of the 30 RC framed projects ranges from 0.81 manday/m^2 to 7.12 manday/m^2 with a median value of 1.47 manday/m^2, while that of the nine SS framed projects ranges from 0.53 to 1.94 manday/m^2 with a median value of 1.04 manday/m^2.

Table 6.37 Statistical description (CP1)

Frame	**Descriptive (CP1)**		**Boxplot**
1. RC	Number	30	
	Median	1.47	
	Mean	2.27	
	Std. Deviation	2.00	
2. SS	Number	9	
	Median	1.04	
	Mean	1.09	
	Std. Deviation	0.38	

- Distribution test on SS group

Table 6.38 shows that the asymptotic significance is 0.33 ($p > 0.05$), which suggests that the distribution of this group of data is normal. Levene’s test is therefore the appropriate test for comparing the difference in CP1 between the RC group and the SS group.

Table 6.38 One-sample Kolmogorov-Smirnov Test (CP1)

Frame	Kolmogorov-Smirnov Test		CP1
SS	N		9
	Normal Parameters	Mean	1.09
		Std. Deviation	0.38
	Kolmogorov-Smirnov Z		0.95
	Asymp. Sig. (2-tailed)		0.33
Distribution is normal.			

- Comparative result

Table 6.39 shows that the difference in CP1 between RC and SS is significant (sig: 0.00). As the mean difference is positive, it is concluded that labor consumption of the RC group is higher than the SS group, which implies that the performance of CP1 of SS framed buildings is significantly better than RC framed buildings.

Table 6.39 Levene's test and t-test for equality (CP1)

CP1	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	5.03	0.03	1.76	37	0.09	1.18
Equal variances not assumed			3.07	34.55	0.00	1.18

6.6.2 Construction speed (CP2)

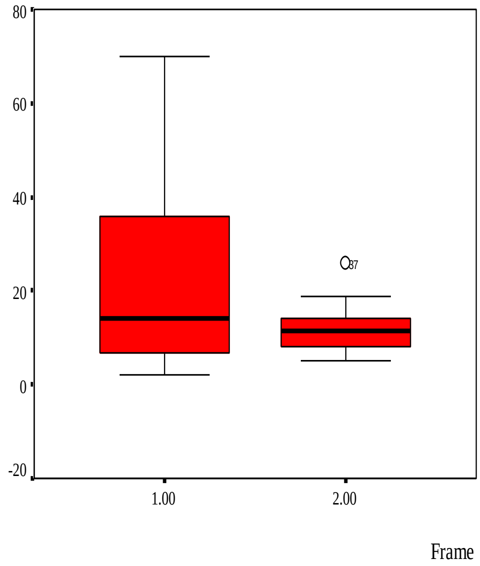
- Description

Construction speed (CP2) is measured by the unit construction duration (day/1000 m^2), as shown in Equation 7.12.

$$\text{CP2}\ (\frac{\text{day}}{1000m^2}) = \frac{\text{duration of structural construction (day)}}{\text{GFA}\ (m^2)} *1000 \ldots\ldots (\textit{Eq. 6.12})$$

Table 6.40 reports the descriptive statistics for CP2. The unit construction duration of the 30 RC framed projects ranges from 1.95 day/1000m^2 to 69.89 day/1000m^2 with a median value of 21.40 day/1000m^2, while that of the nine SS framed projects ranges from 5 day/1000m^2 to 25.71 day/1000m^2 with a median value of 11.33 day/1000 m^2.

Table 6.40 Statistical description (CP2)

Frame	**Descriptive (CP2)**		**Boxplot**
1. RC	Number	30	
	Median	14.01	
	Mean	21.40	
	Std. Deviation	18.67	
2. SS	Number	9	
	Median	11.33	
	Mean	12.59	
	Std. Deviation	6.39	

- Distribution test on SS group

Table 6.41 shows that the asymptotic significance is 0.93 ($p > 0.05$), which suggests that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in CP2 between the RC group and the SS group.

Table 6.41 One-sample Kolmogorov-Smirnov Test (CP2)

Frame	Kolmogorov-Smirnov Test		CP1
SS	N		9
	Normal Parameters	Mean	12.59
		Std. Deviation	6.39
	Kolmogorov-Smirnov Z		0.55
	Asymp. Sig. (2-tailed)		0.93
Distribution is normal.			

- Comparative result

Table 6.42 shows that the difference in CP2 between RC and SS is significant (sig: 0.03). As the mean difference is positive, it is concluded that the unit construction duration of the RC group is greater than the SS group, which implies that the performance of CP2 of SS buildings is significantly better than RC framed buildings.

Table 6.42 Levene's test and t-test for equality (CP2)

CP2	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	T	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	9.40	0.00	1.38	37	0.18	8.81
Equal variances not assumed			2.20	36.10	0.04	8.81

6.6.3 Construction safety (CP3)

- Description

Construction safety is measured by the Accident Severity Rate. According to

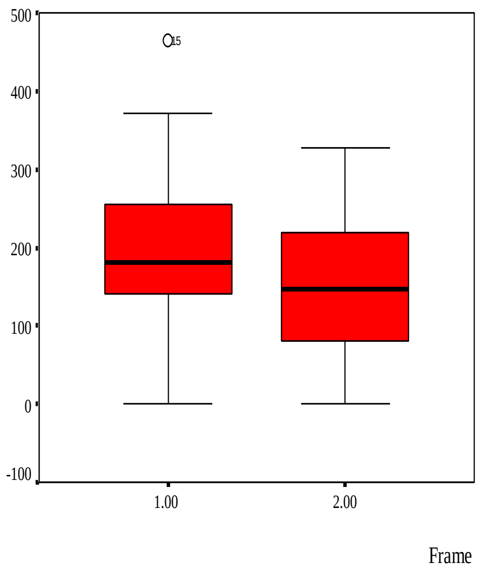
BCA (2011), the Accident Severity Rate (ASR) measures the productivity loss resulting from workplace injuries based on the number of Mandays lost due to workplace accidents. It is calculated using the following formula:

$$\text{Accident Severity Rate (ASR)} = 1{,}000{,}000 * \frac{\text{No. of Mandays Lost To Workplace Accidents}}{\text{No. of Manhours Worked}}$$

……..*(Eq. 6.13)*

Table 6.43 reports the descriptive statistics for CP3. The ASR of the 30 RC framed projects ranges from 0 to 464.00 with a median value of 181.50, while that of the nine SS framed projects ranges from 0 to 328 with a median value of 147.00.

Table 6.43 Statistical description (CP3)

Frame	**Descriptive (CP3)**		**Boxplot**
1. RC	Number	30	
	Median	181.50	
	Mean	207.03	
	Std. Deviation	99.23	
2. SS	Number	9	
	Median	147.00	
	Mean	155.56	
	Std. Deviation	104.32	

- Distribution test on SS group

Table 6.44 shows that the asymptotic significance is 0.97 ($p > 0.05$), which indicates that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in CP3 between the RC group and the SS group.

Table 6.44 One-sample Kolmogorov-Smirnov Test (CP3)

Frame	Kolmogorov-Smirnov Test		CP3
SS	N		9
	Normal Parameters	Mean	155.56
		Std. Deviation	104.32
	Kolmogorov-Smirnov Z		0.50
	Asymp. Sig. (2-tailed)		0.97
Distribution is normal.			

- Comparative result

Table 7.44 shows that the difference in CP3 between RC and SS is not significant (sig: 0.19). It is concluded that the construction safety of SS framed buildings is same with RC framed buildings.

Table 6.45 Levene's test and t-test for equality (CP3)

CP3	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	0.01	0.91	1.35	37	0.19	51.48
Equal variances not assumed			1.31	12.68	0.21	51.48

6.6.4 Construction quality (CP4)

- Description

Construction quality is measured by the CONQUAS score for structural works. With the Quality Standards given By Singapore BCA, it is expected that all projects meet the requirements of Quality Standards for architectural works, for M&E works and for internal finishes. The BCA Construction Quality Assessment System (BCA, 2008) is designed to evaluate construction quality. The CONQUAS score for structural works is employed to represent CP4.

Table 6.46 reports the descriptive statistics for CP4. The CONQUAS score of the 30 RC framed projects ranges from 82 to 100 with a median value of 90, while that of the nine SS framed projects ranges from 90 to 98 with a median value of 97.

Table 6.46 Statistical description (CP4)

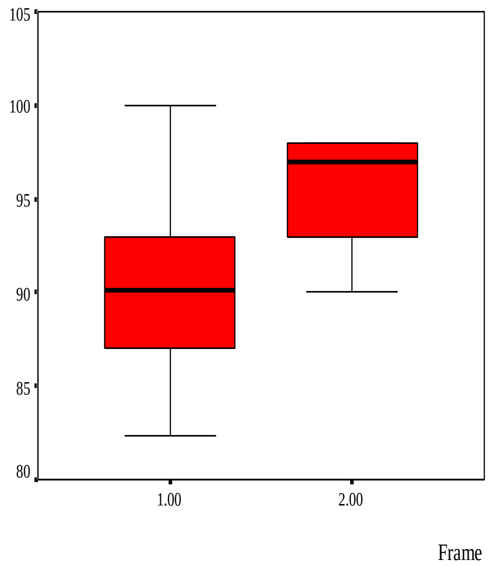
Frame	**Descriptive (CP4)**		**Boxplot**
1. RC	Number	30	
	Median	90	
	Mean	90	
	Std. Deviation	4.55	
2. SS	Number	9	
	Median	97	
	Mean	96	
	Std. Deviation	2.44	

Table 6.47 shows that the asymptotic significance is 0.57 ($p > 0.05$), which suggests that the distribution of this group of data is normal. Levene's test is therefore the appropriate test for comparing the difference in CP4 between the RC group and the SS group.

Table 6.47 One-sample Kolmogorov-Smirnov Test (CP4)

Frame	Kolmogorov-Smirnov Test		CP4
SS	N		9
	Normal Parameters	Mean	95.33
		Std. Deviation	3.08
	Kolmogorov-Smirnov Z		0.78
	Asymp. Sig. (2-tailed)		0.57
Test distribution is normal.			

- Comparative result

Table 6.48 shows that the difference in CP4 between RC and SS is significant (sig: 0.00). As the mean difference is negative, it is concluded that the CONQUAS score of the RC group is lower than the SS group, which implies that the performance of CP4 of SS framed buildings is significantly better than RC framed buildings.

Table 6.48 Levene's test and t-test for equality (CP4)

CP4	Levene's Test for Equality of Variances		t-test for Equality of Means			
	F	Sig.	t	Df	Sig. (2-tailed)	Mean Difference
Equal variances assumed	2.71	0.11	-3.61	37	0.00	-5.74
Equal variances not assumed			-4.94	25.74	0.00	-5.74

6.7 Discussion of results

This section discusses the findings of the importance of the factors, criteria and attributes shown on the hierarchy tree (see Figure 5.3), and the comparison on the performance of RC projects and SS projects.

6.7.1 Importance of the factors, criteria and attributes

The t - test results show that the selection of structural frames is significantly affected by the economic sustainability (EC), environmental sustainability (EN), and constructability (CP) performance of the structural material (see Section 6.3.1). Therefore, all of the three factors (EC, EN, and CP) in the first level of the hierarchy tree (see Figure 5.3) are significantly important and should be considered when making a decision on the selection of structural materials.

This result confirms the relevance of the theory of the firm and rational choice theory (see Section 4.2) in the selection of structural materials, as economic sustainability is a significant indicator to be considered when managers making decisions. In addition, it is found that the two theories do not fully apply to those projects (including HDB projects) because pursuing profits maximization is not the only target for those projects. Developers and contractors also care about environmental sustainability and productivity.

This result also supports the theory of corporate social responsibility (DTI, 2004), which states that private sector organizations should contribute to sustainable development goals (Section 4.3). The result in Section 6.3.2 shows that environmental sustainability is a significantly important factor to be considered when selecting structural material. However, it should be pointed out that Singaporean contractors currently do not exhibit strong 'CSR' although many of them already started to recognize the importance of this issue because of the lack of incentive from government or clients, and may incur additional cost.

Furthermore, this result confirms the relevance of constructability (Section 4.4) in the selection of structural materials.

According to the t-test on the importance of criteria and attributes in Section 6.3.2, it was reported that six (EC3.2, EC4, EC5.3, EN1.2, EN1.4 and EN2) out of the 20 attributes are not significantly important when selecting structural material, while the remaining 14 attributes are significantly important.

Under the factor of economic sustainability (EC), four out of the five criteria proposed in the conceptual framework are significantly important. They are structural costs (EC1), maintenance costs (EC2), non-construction costs (EC3), and additional incomes (EC5).

The end of life costs (EC4) is not significantly important for two reasons. The first reason is that the end of life costs of current projects is normally not paid by the clients, but by other future clients who buy these projects for redevelopment many years later. Thus the end of life costs is not important for the current clients when he has to choose between a SS frame and RC frame. The other reason is that a building generally exists for more than 50 years, and it is hard to predict the costs for demolition at the end of building's life.

Corporate tax (EC3.2), an attribute under EC3, is not significantly important because the use of SS frame or RC frame does not really affect the amount of corporate taxes. Although using SS frame causes higher initial costs than RC frame (EC1), a SS framed project might bring in more incomes (EC5). Therefore, the amount of corporate tax is not related to the structural frame material, but is dependent on corporate profit.

Possible incentive from BCA (EC5.3), an attribute under EC5, is not significantly important for the reason that none of investigated project had earned any incentive from BCA by using RC or SS frame.

Under the factor of environmental sustainability (EN), two attributes (EN1.2 and EN1.4) under material consumption (EN1) and one criterion (EN2) are identified as not significantly important.

The reuse rate of structural material (EN1.2) is not significantly important because it is not common to directly reuse structural elements derived from old projects in Singapore's construction industry. This might be because it is difficult to find old structural elements which have perfect size matched with the current project. Even if such structural elements were found, many stringent tests should be conducted to check whether the materials to be reused have acceptable strength and quality.

Reusability of structural material (EN1.4) is not significantly important for the similar reason described above. As it is hard to directly reuse the structural elements in future projects, both RC elements and SS elements are normally recycled instead of reused after the building is demolished.

CO_2 emission during construction (EN2) in this study refers CO_2 produced by constructing structural elements. EN2 is currently not significantly important for two reasons. The first reason for EN2 being not important in current decision process is that in the latest version of BCA Green Mark, points associated with reduction of CO_2 emission are earned by saving on energy consumption during operation stage of a project, and no points could be given to reduction of CO_2 emission during construction. However, it should be noted that its absence in the Green Mark Scheme is not because it is not important, but because the benchmark to measure and evaluate the extent of reduction of CO_2 emission have not been established. The second reason is that the study on CO_2 emission during construction is still in its infancy stage so the industry and the government do not have sufficient knowledge to build an inventory about CO_2 emission during construction. This also explains why the benchmark for CO_2 emission during construction has not been established. However, given the current trend, this criterion will become more important for the reason given in Section 7.2.1. In addition, during the survey, nine experts pointed out that EN2 will become important for decision on selection of structural materials in the near future when information about CO_2 emission during construction is available. Therefore, EN2 is kept in the DSSSSM for future application.

Under the factor of constructability (CP), all of the four criteria (labor consumption, construction duration, construction safety, and construction quality) are significantly important for selection of structural material. This finding support the principles of constructability given by O'Connor et al. (1986) and Trigunarsyah (2007), which highlighted efficient construction and accessibility of manpower. This result is also consistent with the findings by Ugwu et al. (2004), which pointed out construction safety and quality are implied in constructability concept. The importance of constructability is consistent with the many schemes such as BDAS, CAS, and CONQUAS that are implemented in construction projects in Singapore.

6.7.2 RC and SSs economic sustainability performance

The result in section 6.4.1 showed that using SS frame leads to significantly higher structural costs (EC1) than using RC frame. This finding contradicts Booth (1999) and Liew (2007). The possible reason might be that the structutal costs are reduced by standardizing and industrializing the manufacturing of SS elements in those countries that SS frame is widely used. This also explains the findings by Sim (2007), which reported that in Singapore, when the HDB use steel instead of concrete to construct lift shaft, it achieved an overall cost savings of about 20%. In the recent five years, Singapore HDB has a strong demand for upgrading lift shafts. The huge quantity and ease of standardization make the 20% cost saving possible for lift shaft constrcution. However, the findings by Sim (2007) were not applicable for structural construction of buildings. This is because the elements of HDB lift shafts could be easily prefabricated and installed as they have similar size. The elements of building structures are more complicated than lift shafts. Before this investigation, it was unknown whether using steel frames could save cost instead of using RC frames in Singapore. This study found that using steel frame is still more expensive than using RC frame. The reason might be that SS frame is still not popuplar in Singapore and the benefit of cost reduction from economies of scale cannot be achieved.

Section 6.4.2 showed that maintenance cost (EC2) of SS frame projects is significantly higher than RC. This agrees with Achulitz et.al, (2000) who found that in SS frames, it is necessary to renew or repair the anti-corrosion systems when they expired. This is not happen in RC buildings.

Section 6.4.3 discussed that the financial costs (EC3.1) of SS projects are significantly higher than for RC projects. This result is reasonable, although it has not been identified by previous studies. Financial costs are affected by the amount of loans, loan interest rates, and loan periods. For SS-framed projects, developers need to borrow much more money from the bank because SS-framed buildings involve higher structural costs, which increase the overall costs. Consequently, the financial costs for SS projects are higher.

Section 6.4.4 reported that SS-framed buildings perform significantly better in terms of additional incomes (EC5). The additional incomes are earned through the additional usable areas and the possibility for flexible internal use. For SS-framed buildings, additional use areas are result from the smaller column section size. This supports Zhou's (2005) conclusion that 5% to 8% of use areas were obtained by using steel frames. This study's findings also support Booth's (1999) results that steel buildings had more flexible uses. As SS frame can have wider beam span and fewer columns, the internal space of the building would be more flexible for uses.

6.7.3 RC and SSs environmental sustainability performance

According to the results discussed in Section 6.5.1, SS-framed buildings show significantly better performance on material consumption (EN1) than RC buildings in three aspects: recycling rate, recyclability, and waste rate. In Singapore, SS frames use more recycled materials and have better potential to be recycled at the end of life. The results are consistent with previous studies done by Liew (2007) and the Steel Recycling Institution (2012). The 'recyclability' used in this study has the same definition as NEA's 'recycling rate'. The investigation results of recyclability rate of the two frames are also similar to the recycling rate reported by NEA. In addition, SS elements are prefabricated in factories so that the waste rate for constructing the SS frame is extremely low. This finding supports results provided by Tam and Le (2008) as well as Burgan and Sansom (2006).

In terms of CO_2 emissions (EN2) produced by constructing the two frames, previous studies have provided conflicting results. Some studies (CWC, 1997; Guggemos & Horvath, 2005; Lin, 2003) reported that constructing an SS frame produced less CO_2 than constructing an RC frame; however, Peyroteo (2007) reported the opposite result in Portugal. Furthermore, Eaton and Amato (1998) found no significant differences in CO_2 emissions when constructing the two frames. The current study found that, in Singapore, constructing an SS frame produces significantly less CO_2 than constructing an RC frame because the latter requires more energy due to longer construction duration and uses more machinery for cutting steel bars and formwork, vibrating concrete, and so on.

As discussed in Section 6.5.3, building an SS frame consumes significantly less water (EN3) than building an RC frame because of the dry construction. This finding supports Zhou's (2005) study in China.

In terms of construction noise (EN4), respondents indicated a similar degree of noise when constructing the two frames. The reason might be that construction noise has to be controlled (maintained under a certain decibel level) due to Singapore BCA law. Although the noise is produced from various sources when constructing RC and SS, respondents of this study rated a similar level of noise based on their perceptions and results from decibel meters.

6.7.4 RC and SSs constructability performance

This study found that constructing an SS frame consumes less manpower than an RC frame for three reasons. First, almost all SS elements are prefabricated by machines in factories. Second, the installation processes for SS frames are simpler than the construction processes for RC frames (refer to Chapter 3). Finally, the SS frame causes less construction duration, which leads to a reduction of total man days.

Supporting previous studies (Aghayere & Vigil, 2009; Booth, 1999; Burgan & Sansom, 2006; Langdon et al., 2002; Liew, 2007; Silva, 2005), this study also found that constructing an SS frame is significantly faster than constructing an RC frame in Singapore. However, the difference of construction duration is not great as most SS projects have a reinforced concrete core that is constructed prior to the frame so that the frame can be connected to it. If the core is not constructed fast enough, the SS contractors have to stop their work and wait for the core to be completed. This situation is common in Singapore SS projects. If this problem could be solved properly, SS frames might show a dramatic advantage in terms of construction speed.

Accident Severity Rate (ASR) was employed to investigate the performance of construction safety. Section 6.6.3 showed that the ASR of SS projects is similar to that of RC projects. This finding does not support the statement that SS frames have better construction safety performance than RC frames during construction (Burgan & Sansom, 2006; Silva, 2005). Silva (2005) argued that prefabrication eliminates many risks of on-site production. Aghayere and Vigil (2009) concurred, claiming that the high ductility of SS frames enables adequate warning of any impending collapse. In addition, some respondents in the current study mentioned that SS frames consumed less manpower so that the risk of an accident occurring was reduced. However, several respondents pointed out that the risk of constructing RC frames can be eliminated by using a scaffolding system and dust screen.

Section 6.6.4 pointed out that SS frames have significantly better construction quality (CP4) than RC frames in Singapore as SS projects earned a significantly higher CONQUAS score than RC projects. This is consistent with the findings of Liew (2007) and Silva (2005), who reported that SS had better quality because of steel's inherent properties. In addition, some respondents in this study said that this might be because the standardization and prefabrication of SS elements ensured the quality of SS frames.

6.8 Summary

Data from 30 RC and nine SS framed building projects were obtained from the fieldwork. From the statistical analysis, 14 attributes that are significantly important when a decision is to be made on the type of structural materials are found (see section 6.3). Six (EC3.2, EC4, EC5.3, EN1.2, EN1.4 and EN2) out of the 20 attributes are not significantly important.

Objective 1 of this study is to investigate the economic, environmental and constructability performance of RC framed buildings. It was found that the structural cost of the 30 RC-framed projects ranges from S$166.70/m^2 to

S\$1,823.60/m^2 with a median value of S\$758.60/m^2. The maintenance cost is zero. The financial costs range from S\$1.69/m^2 to S\$33.74/m^2 with a median value of S\$10.79/ m^2. The proportion of area occupied by the columns ranges from 2.00% to 4.00%, with a median value of 2.55%. The flexibility of internal space ranges from 2 to 5 with a median value of 4. The recycling rate of the 30 RC-framed projects ranges from 11.83% to 28.30% with a median value of 22.93%. The recyclability rate ranges from 60% to 98% with a median value of 85%. The waste rate during construction stage ranges from 3% to 10% with a median value of 6%. The CO_2 emission during construction stage ranges from 0.80 kg/m^2 to 211.80 kg/m^2 with a median value of 24.40 kg/m^2. The water consumption during construction stage ranges from 133.20 l/m^2 to 11,099.30 l/m^2 with a median value of 1,143.25 l/m^2. The rating of noise ranges from 2 to 5 with a median value of 3. The unit labor consumption of the 30 RC framed projects ranges from 0.81 manday/m^2 to 7.12 manday/m^2 with a median value of 1.47 manday/m^2. The unit construction duration ranges from 1.95 day/1000m^2 to 69.89 day/1000m^2 with a median value of 21.40 day/1000m^2. The ASR ranges from 0 to 464.00 with a median value of 181.50. The CONQUAS score ranges from 82 to 100 with a median value of 90.

Objective 2 is to investigate the economic, environmental and constructability performance of SS framed buildings. It was found that the structural cost of the nine SS-framed projects ranges from S\$375.00/ m^2 to S\$4,285.70/m^2 with a median value of S\$1,055.80/m^2. The maintenance costs range from S\$34.60/m^2 to S\$328.10/m^2 with a median value of S\$221.70/m^2. The financial costs range from S\$ 14.74/ m^2 to S\$274.55/ m^2 with a median value of S\$59.06/ m^2. The proportion of area occupied by the columns ranges from 1.50% to 2.00%, with a median value of 1.78%. The flexibility of internal space ranges from 4 to 5 with a median value of 5. The recycling rate of the nine SS framed projects ranges from 37.7% to 43.93% with a median value of 39.57%. The recyclability rate ranges from 90% to 100% with a median value of 98%. The waste rate during construction stage ranges from0 to 5% with a median value of 3%. The CO_2 emission during construction stage ranges from 0.10 kg/m^2 to 91.00 kg/m^2 with a median value of 11.69 kg/m^2. The water consumption during construction stage ranges from 0 to 7.10 l/m^2 with a median value of 0.20 l/m^2. The rating of noise produced in construction stage ranges from 1 to 4 with a median value of 3. The unit labor consumption of the nine SS framed projects ranges from 0.53 to 1.94 manday/m^2 with a median value of 1.04 manday/m^2. The unit construction duration ranges from 5 day/1000m^2 to 25.71 day/1000m^2 with a median value of 11.33 day/1000 m^2. The ASR ranges from 0 to 328 with a median value of 147.00. The CONQUAS score ranges from 90 to 98 with a median value of 97.

Objective 3 is to compare the economic, environmental and constructability performance between RC framed buildings and SS framed buildings. It was found that first, both RC-framed projects and SS-framed projects are similar in performance in terms of noise (EN4) and construction safety (CP3). Second, RC-framed projects perform significantly better than SS-framed projects in terms of structural costs (EC1), maintenance costs (EC2), and financial costs (EC3.1). Finally, SS-framed projects perform significantly better than RC-framed projects in terms of Additional usable area (EC5.1), flexibility (EC5.2), recycling rate (EN1.1), recyclability (EN1.3), waste rate (EN1.5), CO_2 emissions during construction (EN2), water consumption (EN3), labor efficiency (CP1), construction speed (CP2), and construction quality (CP4).

CHAPTER 7 DSSSSM CONSTRUCTION, APPLICATION AND VALIDATION

7.1 Introduction

This chapter presents the decision support system for structural material selection which may be used to evaluate and select structural frame materials for building projects. It addressed objective 4 of the study. Detailed DSSSSM construction, including the weights of attributes and the method of rating each attribute, is provided in section 7.2. The application process of the decision support system for the selection of structural materials (DSSSSM) is explained in Section 7.3, and the system is presented in the form of an MS Excel spreadsheet in Appendix 5. Section 7.4 reports the DSSSSM's validation process. Four new sets of data were individually input into the DSSSSM and validated by investigating the consistency of conclusions drawn by the DSSSSM and the decisions made by experts in reality. Experts' comments on the application of DSSSSM are presented in Section 7.5.

7.2 DSSSSM construction

In Section 5.5.1.2, the MAVT method was shown to be the most suitable method for selecting the frame material of buildings. The steps of constructing the decision support system for selecting structural frame materials based on MAVT are:

- Establish the hierarchy tree,
- Build the weights system,
- Develop the rating system for attributes and criteria, and
- Form the aggregation formula.

7.2.1 Establishment of hierarchy tree

In this study, those attributes identified as important when selecting structural frame materials were kept in the decision hierarch tree. Six out of 20 attributes (as shown in Figure 5.3) were found to be non-important (see Section 6.3.2). Five of these attributes (EC3.2, EC4, EC5.3, EN1.2, and EN1.4) were removed from the decision hierarchy tree. EN2 was kept in the hierarchy tree, although the importance of EN2 did not pass the *t*-test, because CO_2 emissions are an essential criterion of the green building label scheme in Singapore. Although CO_2 emissions produced by RC and SS frames are currently not included in this scheme due to the lack of relative studies, trends indicate that EN2 will be added into the scheme and, therefore, become important for decision making in the industry in the near future.

In addition, attributes whose performance had no significant difference between RC projects and SS projects were removed from decision tree. According to comparative result of performance (Sections 6.4 to 6.6), the performance of EN4 (noise) and CP3 (construction safety) showed no significant difference and were thus removed.

After removing those non-important attributes and criteria with similar performance between RC and SS projects, a refined decision hierarchy tree was developed, as shown in Figure 7.1.

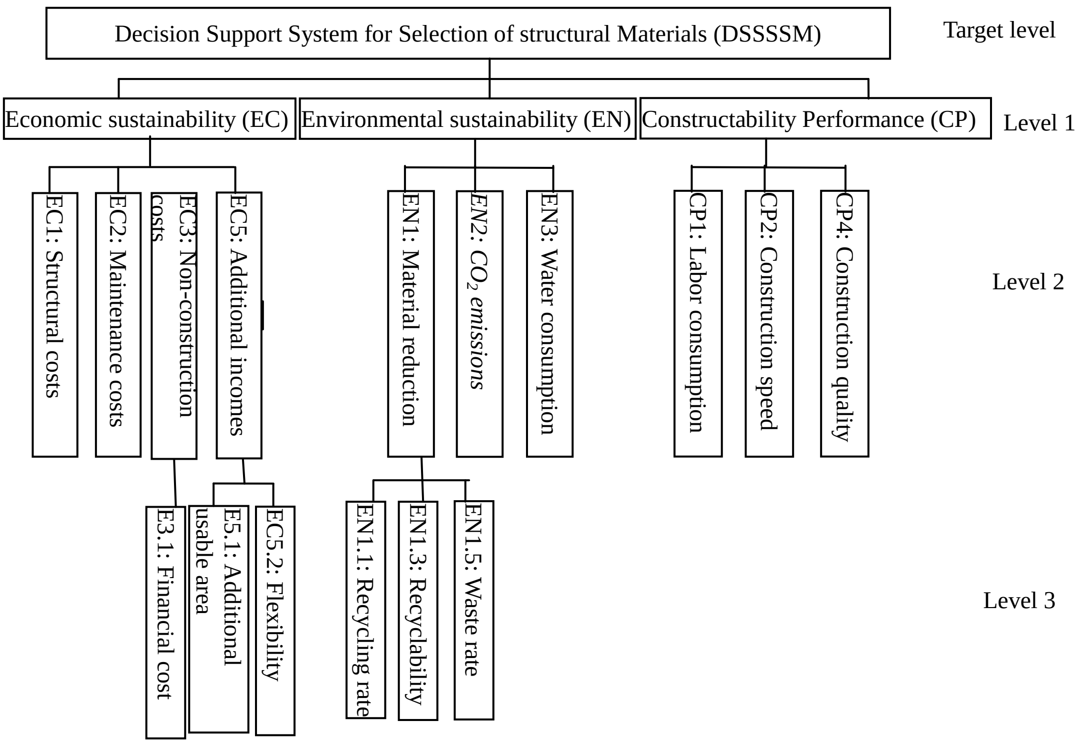


Figure 7.1 Decision hierarchy tree of DSSSSM

7.2.2 *Development of weighting system*

This decision support system provides two weighting systems to assist users in making decisions on the selection of structural materials—a defined weighting system and a customized system—to provide an applicable decision support system for users regardless of whether they have their own priorities of factors, criteria, and/or attributes. The defined weighting system is helpful for users who are not sure about their priorities. The customized weighting system might help users develop their own weights if they have clear priorities for factors, criteria, and/or attributes that are different from priorities provided by this study.

7.2.2.1 Defined weighting system

- Defined weights of factors

As described in Section 5.5.2, the AHP method was used to compute the importance of factors on the first level of the hierarchy tree.

Step 1: Build consolidated AHP input matrix (A)

Firstly, each of the 39 sets of data of importance of factors was transformed to an original AHP input Matrix (A_k). Then, the 39 original AHP input matrixes were consolidated into one AHP input matrix ($\mathbf{A}$) by calculating the geometric mean of each vector $\alpha_{\mathbf{ij}}$ (refer to Equation 5.2). The AHP input Matrix (A) is shown in Table 7.1.

Table 7.1 AHP input Matrix (A)

A	EC	EN	CP
EC	1	2.970	1.427
EN	0.337	1	0.402
CP	0.701	2.490	1

Step 2: Normalization and calculation of Eigen vector

Equation 5.3 to 5.6 were used to normalize he consolidated AHP input matrix

A to normalized matrix | A |. Then the Eigen vectors were derived by using Equation 5.7 and 5.8. Table 7.2 shows the normalized matrix and results of Eigen vectors. The three Eigen vectors were used as the defined weights for the three factors. From the right column, it can be seen that 0.485 is the defined weight for EC, 0.154 is the defined weight for EN, and 0.361 the defined weight for CP.

Table 7.2 Normalized matrix and defined weights of factors

Normalization $\lvert A \rvert$	EC	EN	CP	Sum	Eigen vector, weights $\omega_1, \omega_2, \omega_3$
EC	0.491	0.460	0.504	1.455	0.485
EN	0.165	0.155	0.142	0.462	0.154
CP	0.344	0.385	0.354	1.083	0.361

- Defined weights of criteria and attributes

A 1-5 Likert scale was used to investigate the importance of criteria on the second level and attributes on the third level of the hierarchy tree. The defined weights of criteria and attributes were calculated by inputting the 39 sets of data into Equations 5.10 to 5.12. Merged with results of Table 7.2, Table 7.3 reports the defined weights system for this DSSSSM.

Table 7.3 Defined weighting system of DSSSSM

No.	**Factors, criteria and attributes**	**Mean importance** a_j/b_j *(Eq.5.12)*	**Attribute weight** a_{ij} *(Eq.5.11)*	**Criterion weight** ω_{ij} *(Eq.5.10)*	**Factor weight** ω_i *(Table 7.2)*
1	**Factor1: Economical sustainability (EC)**				**0.485**
1.1	Criterion 1.1: Structural cost (EC1)	4.385		0.313	
1.2	Criterion 1.2: Maintenance cost (EC2)	3.308		0.236	
1.3	Criterion 1.3: Non-construction cost (EC3)	3.308		0.236	
1.3.1	*Financial costs(EC3.1)*		1		
1.4	Criterion 1.4: Additional incomes (EC5)	3.000		0.214	
1.4.1	Additional usable area (EC5.1)	3.256	0.512		
1.4.2	Flexibility (EC5.2)	3.103	0.488		
2	**Factor2: Environmental sustainability (EN)**				**0.154**
2.1	Criterion 2.1:Mateiral consumption (EN1)	3.179		0.528	
2.1.1	*Recycling rate (EN1.1)*	3.128	0.362		
2.1.2	*Recyclability (EN1.3)*	2.718	0.315		
2.1.3	*Waste rate (EN1.5)*	2.795	0.323		
2.2	Criterion 2.2: CO_2 emissions (EN2)	2.846		0	
2.3	Criterion 2.3: Water consumption (EN3)	3.949		0.472	
3	**Factor 3: Constructability Performance (CP)**				**0.361**
3.1	Criterion 3.1: Labor consumption (CP1)	3.949		0.309	
3.2	Criterion 3.2: Construction duration (CP2)	4.513		0.353	
3.3	Criterion 3.3: Construction quality (CP4)	4.333		0.339	

7.2.2.2 Customized weighting system

When using this DSSSSM, some users might need to replace the defined importance of one or several attributes, criteria, and even factors with their own. For example, the priority of construction duration (CP2) for a typical project might be extremely high because a very tight construction period is required by the client. To meet this demand, a customized weighting system is also provided in this study so that users can develop their own weights by inputting their ratings of importance of attributes into the customized weighting system.

The same methodologies for developing the defined weighting system were used to compute the weights of customized weighting system. The difference between the two systems is that, in the defined weighting system, users do not evaluate the importance of any factor, criteria, or attribute, whereas in customized weighting system users input their own ratings.

To assist users in computing the customized weights in an automatic way, all the information that users need to fill in and the equations described in Section 5.5.2 were preloaded into a Microsoft Excel spread sheet (see Appendix 5: Weighting system).

Once the customized weighting system is chosen, users first go through the defined importance of factors, criteria, and attributes. If they disagree on any defined importance, they can type their rating into the corresponding block of the weighting system (see Appendix 5.1). The weights of factors, criteria, and attributes (called customized weights) will then be automatically computed and given at the bottom of the sheet.

7.2.3 Development of rating system

Following the MAVT process, the next step in the DSSSSMwas to evaluate an optional frame (SS or RC) against each criterion or attribute. Method 1 (Quartiles + Linear interpolation) was used to evaluate EC1, EC3.1, EC5.1, EN1.1, EN1.3, EN1.5, EN2, EN3, CP1, CP2, and CP4 (refer to Section 5.5.2.1). However, method 1 was unsuitable for EC2 and EC5.2 because the performance of the two attributes is discrete distribution, meaning the assumption of the linear interpolation is not applicable. Therefore, the summated rating method (refer to Section 5.5.2.2) was used to evaluate EC5.2, and special rating methods were developed to evaluate EC2.

In this study, a percentile score (0 to 100 scale) was used to rate the performance of attributes and criteria. This method was proposed by Motowidleo and Van Scotter (1994) to evaluate the ratee's likelihood of fulfilling attributes. In addition, Kometa (1995) used percentile to rate the level to which rates satisfied an attribute. Similar methods such as a normalized score (scale of 0 to 1) and decile score (scale of 0 to 10) were not used because they are too narrow to show small differences.

The rating methods used to evaluate each criterion or attribute are shown in Table 7.4.

Table 7.4 Methods of rating criteria and attributes for DSSSSM

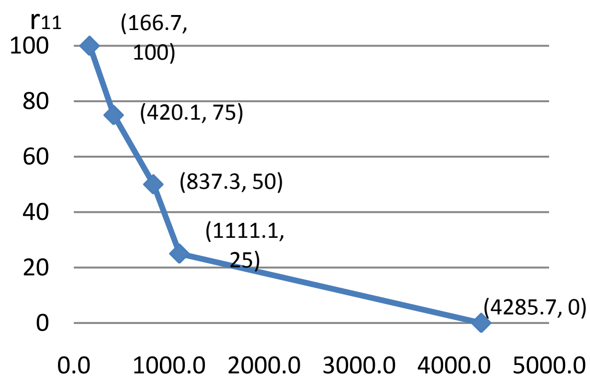
No.	Factors, criteria and attributes	Rating methods
1	**Factor1: Economical sustainability(EC)**	
1.1	Criterion 1.1: Structural cost (EC1)	Quartiles +Linear interpolation
1.2	Criterion 1.2: Maintenance cost (EC2)	RC frame: Score=100 SS frame: Score= 0
1.3	Criterion 1.3: Non-construction cost (EC3)	
1.3.1	*Financial costs(EC3.1)*	Quartiles +Linear interpolation
1.4	Criterion 1.4: Additional incomes (EC5*)*	
1.4.1	*Additional usable area (EC5.1)*	Quartiles +Linear interpolation
1.4.2	*Flexibility of utilizing internal space(EC5.2)*	1= "extremely unsatisfied", Score= 0 2= "unsatisfied", Score= 25 3="neutral", Score= 50 4= "good", Score= 75 5=" outstanding", Score=100

No.	Factors, criteria and attributes	Rating methods
2	**Factor2: Environmental sustainability (EN)**	
2.1	Criterion 2.1:Mateiral consumption (EN1)	
2.1.1	*Recycling rate (EN1.1)*	Quartiles +Linear interpolation
2.1.2	*Recyclability (EN1.3)*	Quartiles +Linear interpolation
2.1.3	*Waste rate (EN1.5)*	Quartiles +Linear interpolation
2.2	Criterion 2.2: CO2 emission (EN2)	Quartiles +Linear interpolation
2.3	Criterion 2.3: Water consumption (EN3)	Quartiles +Linear interpolation
3	**Factor 3: Constructability Performance (CP)**	
3.1	Criterion 3.1: Labor consumption (CP1)	Quartiles +Linear interpolation
3.2	Criterion 3.2: Construction duration (CP2)	Quartiles +Linear interpolation
3.3	Criterion 3.3: Construction quality (CP3)	Quartiles +Linear interpolation

7.2.3.1 Rating of structural cost (EC1)

After obtaining the raw data from the survey, the 39 sets of data of structural costs were converted to the unit cost (S$/m^2), and the quartiles method was used to locate the hinges. A score range between two hinges was assumed to be linearly distributed between two hinges. The rating chart is shown in Table 7.5.

Table 7.5 Rating chart of EC1

EC1		Performance V_{11} (S\$/m^2)	Quartiles
Minimum		166.7	
Hinges	25% (H1)	420.1	
	50% (H2)	837.3	
	75% (H3)	1,111.1	
Maximum		4,285.7	

Then the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

$$r_{11} = \mathrm{f}(v_{11}) = \begin{cases} 100, & v_{11} \in (0, 166.7) \\ 100 - 0.0987 * (v_{11} - 166.7), & v_{11} \in (166.7, 420.1) \\ 75 - 0.0599 * (v_{11} - 420.1), & v_{11} \in (420.1, 837.3) \\ 50 - 0.0913 * (v_{11} - 837.3), & v_{11} \in (837.3, 1111.1) \\ 25 - 0.0079 * (v_{11} - 1111.1), & v_{11} \in (1111.1, 4285.7) \\ 0, & v_{11} \in (4285.7, \infty) \end{cases} \quad ..(Eq.\ 7.1)$$

7.2.3.2 Rating of maintenance cost (EC2)

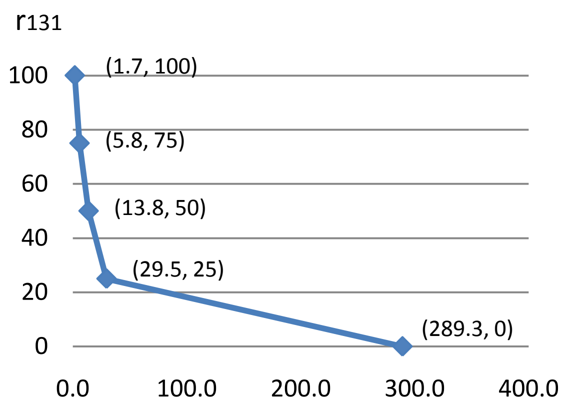
It was resulted from section 6.4.2 that no maintenance cost occurred for those RC framed buildings. All SS framed buildings need restoration of fire protection and anti-corrosion during the operation stage. The rating method for EC2 is given in Eq.7.2.

$$r_{12} = \begin{cases} 100, & \text{RC frame} \\ 0, & \text{SS frame} \end{cases} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (Eq.\ 7.2)$$

7.2.3.3 Rating of financial cost (EC3.1)

The 39 sets of raw data of financial costs were converted to the unit cost (S\$/m^2). Quartiles method was used to locate the hinges. A score range of 25 was assumed to be linearly distributed between two hinges. The rating chart of EC3.1 is shown in Table 7.6.

Table 7.6 Rating chart of EC3.1

EC3.1		Performance v_{131} (S\$/m^2)	Quartiles
Minimum		1.7	
Hinges	25% (H1)	5.8	
	50% (H2)	13.8	
	75% (H3)	29.5	
Maximum		289.3	

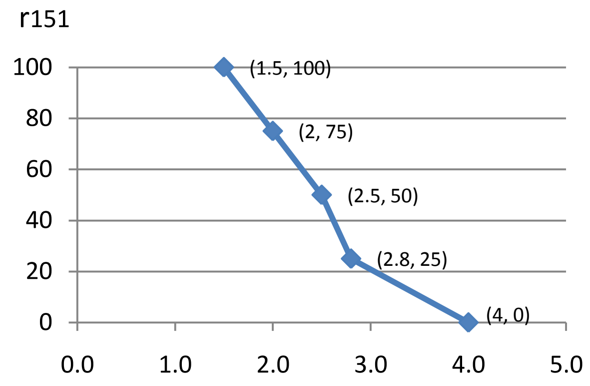
Using Equation 5.17, the rating function is given as follows:

$$r_{131} = \mathrm{f}(v_{131}) = \begin{cases} 100, \ v_{131} \in (0, 1.7) \\ 100 - 0.0987 * (v_{131} - 1.7), \ v_{131} \in (1.7, 5.8) \\ 75 - 6.0386 * (v_{131} - 5.8), \ v_{131} \in (5.8, 13.8) \\ 50 - 3.1368 * (v_{131} - 13.8), \ v_{131} \in (13.8, 29.5) \\ 25 - 1.5883 * (v_{131} - 29.5), v_{131} \in (29.5, 289.3) \\ 0, \ v_{131} \in (\ 289.3, \infty) \end{cases} \text{......}(Eq.\ 7.3)$$

7.2.3.4 <u>Rating of additional area (EC5.1)</u>

After obtaining the raw data from the survey, quartiles method was used to locate the hinges. The rating chart of EC 5.1 is shown in Table 7.7.

Table 7.7 Rating chart of EC5.1

EC5.1		Performance v_{151} (%)	Quartiles
Minimum		1.5	
Hinges	25% (H1)	2.0	
	50% (H2)	2.5	
	75% (H3)	2.8	
Maximum		4.0	

Then the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

$$r_{151} = \mathrm{f}(v_{151}) = \begin{cases} 100, & v_{151} \in (0,\ 1.5) \\ 100 - 50 * (v_{151} - 1.5), & v_{151} \in (1.5,\ 2) \\ 75 - 50 * (v_{151} - 2), & v_{151} \in (2,\ 2.5) \\ 50 - 83.333 * (v_{151} - 2.5), & v_{151} \in (2.5, 2.8) \\ 25 - 20.833 * (v_{151} - 2.8), & v_{151} \in (2.8, 4) \\ 0, & v_{151} \in (\ 4, 100) \end{cases} \quad \text{......(Eq. 7.4)}$$

7.2.3.5 Rating of Flexibility (EC5.2)

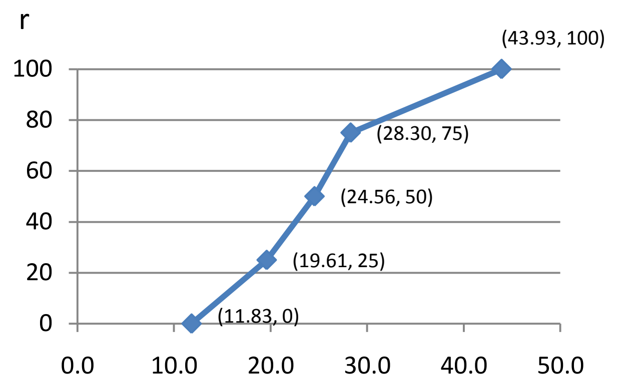
EC5.2 was measured by 1-5 scale, where 1 is “extremely unsatisfactory”, 2 is “unsatisfactory”, 3 is “neutral”, 4 is “very good”, and 5 is “outstanding”. It is proper to distributed Score 0-100 on the five points normally.

$$r_{152} = \begin{cases} 100, & v_{152} = 5 \\ 75, & v_{152} = 4 \\ 50, & v_{152} = 3 \\ 25, & v_{152} = 2 \\ 0, & v_{152} = 1 \end{cases} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{..(Eq. 7.5)}$$

7.2.3.6 Rating of recycling rate (EN1.1)

The recycling rates of the 39 buildings were separately computed using Equation 6.5 and Equation 6.6. Based on these data, quartiles method was used to locate the hinges. The rating chart is shown in Table 7.8.

Table 7.8 Rating chart of EN1.1

EN1.1		Performance v_{211} (%)	Quartiles
Minimum		11.83	
Hinges	25% (H1)	19.61	
	50% (H2)	24.56	
	75% (H3)	28.3	
Maximum		43.93	

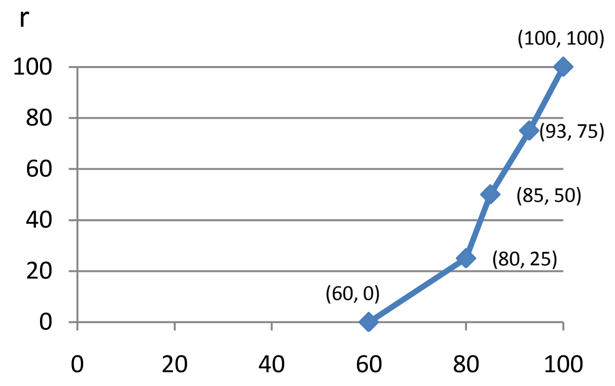
Then the performance values of minimum, hinges, and maximum were put into Equation 5.18. The rating function was deduced as follows:

$$r_{211} = f(v_{211}) = \begin{cases} 0, & v_{211} \in (0, 18.83) \\ 3.2134 * (v_{211} - 18.83), & v_{211} \in (18.83, 19.61) \\ 25 + 5.0505 * (v_{211} - 19.61), & v_{211} \in (19.61, 24.56) \\ 50 + 6.6845 * (v_{211} - 24.56), & v_{211} \in (24.56, 28.3) \\ 75 + 1.5995 * (v_{211} - 28.3), & v_{211} \in (28.3, 43.93) \\ 100, & v_{211} \in (43.93, 100) \end{cases} \quad \text{...}(Eq.\ 7.6)$$

7.2.3.7 Rating of recyclability (EN1.3)

After obtaining the raw data from the survey and input into SPSS program, quartiles method was used to locate the hinges. The rating chart is shown in Table 7.9.

Table 7.9 Rating chart of EN1.3

EN1.3		Performance v_{213} (%)	Quartiles
Minimum		60	
Hinges	25% (H1)	80	
	50% (H2)	85	
	75% (H3)	93	
Maximum		100	

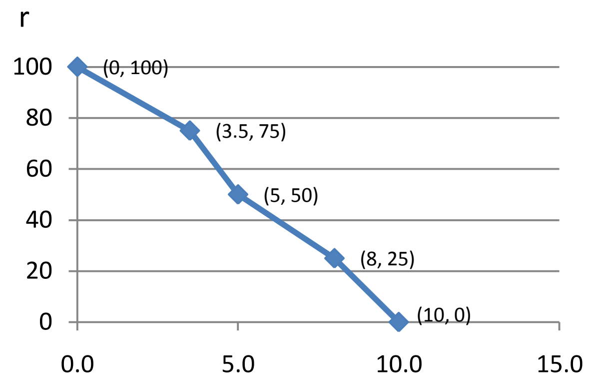
Then the performance values of minimum, hinges, and maximum were put into Equation 5.18. The rating function was deduced as follows:

$$r_{212} = \mathrm{f}(v_{213}) = \begin{cases} 0, \ v_{213} \in (0, 60) \\ 1.25 * (v_{213} - 60), \ v_{213} \in (60, 80) \\ 25 + 5 * (v_{213} - 80), \ v_{213} \in (80, 85) \\ 50 + 3.125 * (v_{213} - 85), \ v_{213} \in (85, 93) \\ 75 + 3.5714 * (v_{213} - 1111.1), \ v_{213} \in (93, 100) \end{cases} \quad \text{......}(\mathit{Eq.\ 7.7})$$

7.2.3.8 Rating of waste (EN1.5)

After obtaining the raw data from the survey and inputting them into SPSS program, quartiles method was used to locate the hinges. The rating chart is shown in Table 7.10.

Table 7.10 Rating chart of EN1.5

<table>
<tr><th colspan="2">EN1.5</th><th>Performance v_{215} (%)</th><th>Quartiles</th></tr>
<tr><td colspan="2">Minimum</td><td>0.0</td><td rowspan="5">
</td></tr>
<tr><td rowspan="3">Hinges</td><td>25% (H1)</td><td>3.5</td></tr>
<tr><td>50% (H2)</td><td>5.0</td></tr>
<tr><td>75% (H3)</td><td>8.0</td></tr>
<tr><td colspan="2">Maximum</td><td>10.0</td></tr>
</table>

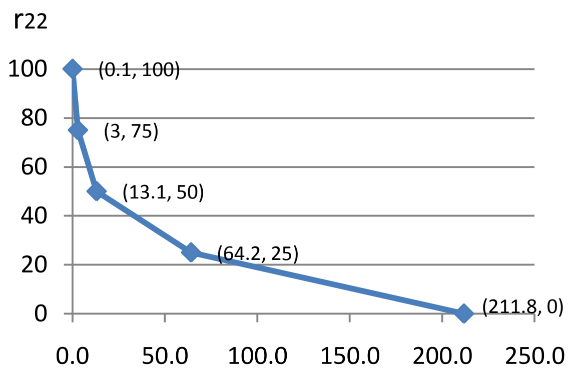
Finally the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

$$r_{213} = \mathrm{f}(v_{215}) = \begin{cases} 100 - 7.1429 * v_{215}, & v_{215} \in (0, 3.5) \\ 75 - 16.6667 * (v_{215} - 3.5), & v_{215} \in (3.5, 5) \\ 50 - 8.3333 * (v_{215} - 5), & v_{215} \in (5, 8) \\ 25 - 12.5 * (v_{215} - 10), & v_{215} \in (8, 10) \\ 0, & v_{215} \in (10, 100) \end{cases} \quad \text{......}(Eq.\ 7.8)$$

7.2.3.9 Rating of CO_2 emission (EN2)

After obtaining the raw data of energy consumption from the survey, the amount of CO_2 emission produced by constructing the structural elements of each project was computed using Equation 6.7 to 6.11. Then the 39 sets data of CO_2 emission were converted to the unit emission (kg/m^2). Quartiles method was used to locate the hinges. The rating chart is shown in Table 7.11.

Table 7.11 Rating chart of EN2

EN2		Performance v_{22} (kg/m^2)	Quartiles
Minimum		0.1	
Hinges	25% (H1)	3.0	
	50% (H2)	13.1	
	75% (H3)	64.2	
Maximum		211.8	

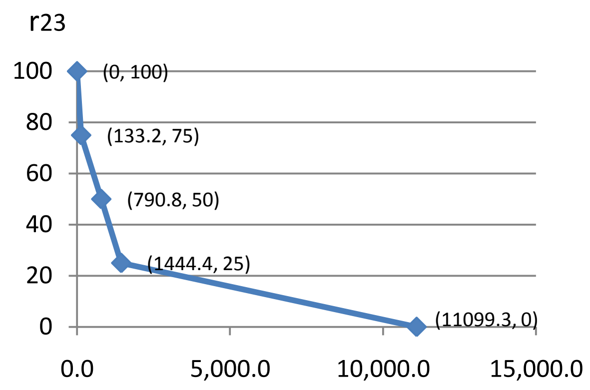
Finally, the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

$$r_{22} = \mathrm{f}(v_{22}) = \begin{cases} 100, & v_{22} \in (0, 0.1) \\ 100 - 0.0987 * (v_{22} - 0.1), & v_{22} \in (0.1, 3) \\ 75 - 8.6207 * (v_{22} - 3), & v_{22} \in (3, 13.1) \\ 50 - 0.4892 * (v_{22} - 13.1), & v_{22} \in (13.1, 64.2) \\ 25 - 0.1694 * (v_{22} - 64.2), & v_{22} \in (64.2, 211.8) \\ 0, & v_{22} \in (211.8, \infty) \end{cases} \quad \text{...(Eq. 7.9)}$$

7.2.3.10 <u>Rating of water consumption (EN3)</u>

After obtaining the raw data from the survey, the water consumption of the 39 buildings was separately converted to the unit dimension (l/m^2). Quartiles method was used to locate the hinges. The rating chart is shown in Table 7.12.

Table 7.12 Rating chart of EN3

EN3		Performance v_{23} (l/ m^2)	Quartiles
Minimum		0.0	
Hinges	25% (H1)	133.2	
	50% (H2)	790.8	
	75% (H3)	1,444.4	
Maximum		11,099.3	

Finally, the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

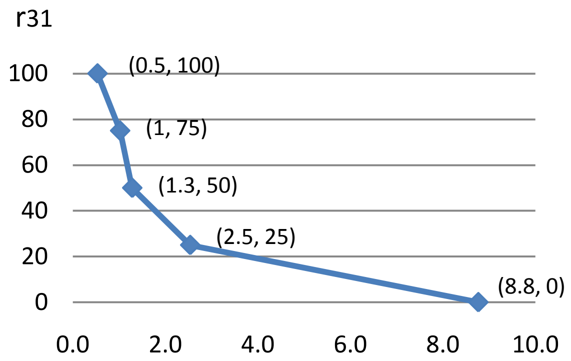
$$r_{23} = \mathrm{f}(v_{23}) = \begin{cases} 100 - 0.1877 * v_{23}, \quad v_{23} \in (0, 133.2) \\ 75 - 0.0380 * (v_{23} - 133.2), v_{23} \in (133.2, 790.8) \\ 50 - 0.0382 * (v_{23} - 790.8), v_{23} \in (790.8, 1444.4) \\ 25 - 0.0026 * (v_{23} - 1444.4), v_{23} \in (1444.4, 11099.3) \\ 0, \quad v_{23} \in (11099.3, \infty) \end{cases}$$

……(Eq. 7.10)

7.2.3.11 Rating of labor consumption (CP1)

After being obtained from the survey, the labor consumption of the 39 buildings was separately converted to the unit dimension (manday/m^2). Quartiles method was used to locate the hinges. The rating chart is shown in Table 7.13.

Table 7.13 Rating chart of CP1

CP1		Performance v_{31} (Manday/m^2)	Quartiles
Minimum		0.5	
Hinges	25% (H1)	1.0	
	50% (H2)	1.3	
	75% (H3)	2.5	
Maximum		8.8	

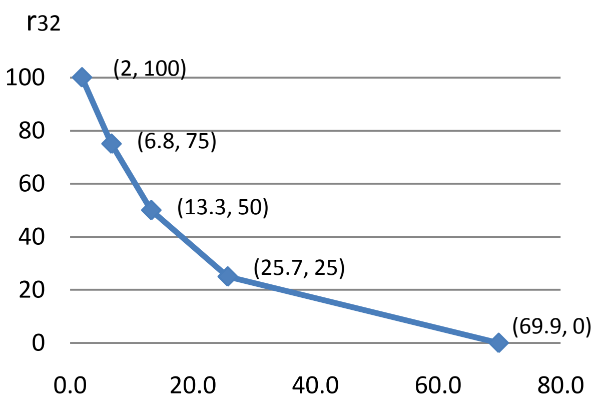
Finally, the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follows:

$$r_{31} = f(v_{31}) = \begin{cases} 100, & v_{31} \in (0, 0.5) \\ 100 - 51.1247 * (v_{31} - 0.5), & v_{31} \in (0.5, 1) \\ 75 - 95.4198 * (v_{31} - 1), & v_{31} \in (1, 1.3) \\ 50 - 19.9362 * (v_{31} - 1.3), & v_{31} \in (1.3, 2.5) \\ 25 - 4.0115 * (v_{31} - 2.5), & v_{31} \in (2.5, 8.8) \\ 0, & v_{31} \in (8.8, \infty) \end{cases} \quad \ldots\ldots\ldots \textit{(Eq. 7.11)}$$

7.2.3.12 Rating of construction speed (CP2)

After being obtained from the survey, the construction duration of the 39 buildings was separately converted to the unit dimension (day/1000m^2). Quartiles method was used to locate the hinges. The rating chart is shown in Table 7.14.

Table 7.14 Rating chart of CP2

CP2		Performance v_{32} (Day/1000 m^2)	Quartiles
Minimum		2.0	
Hinges	25% (H1)	6.8	
	50% (H2)	13.3	
	75% (H3)	25.7	
Maximum		69.9	

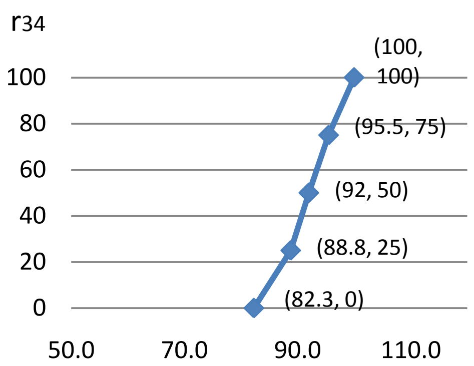
Finally, the performance values of minimum, hinges, and maximum were put into Equation 5.17. The rating function was deduced as follow:

$$r_{32} = \mathrm{f}(v_{32}) = \begin{cases} 100, & v_{32} \in (0, 2) \\ 100 - 5.1975 * (v_{32} - 2), & v_{32} \in (2,\ 6.8) \\ 75 - 3.8521 * (v_{32} - 6.8), & v_{32} \in (6.8, 13.3) \\ 50 - 2.0046 * (v_{32} - 13.3), & v_{32} \in (13.3, 25.7) \\ 25 - 0.5659 * (v_{32} - 25.7), & v_{32} \in (25.7, 69.9) \\ 0, & v_{32} \in (69.9, \infty) \end{cases} \quad \text{......}\textit{(Eq. 7.12)}$$

7.2.3.13 <u>Rating of construction quality (CP4)</u>

After being obtained from the survey, the CONQUAS scores of the 39 projects were inputted into SPSS program to locate the hinges using Quartiles method. The rating chart is shown in Table 7.15.

Table 7.15 Rating chart of CP4

CP4		Performance v_{33} (CONQUAS 0-100)	Quartiles
Minimum		82.3	
Hinges	25% (H1)	88.8	
	50% (H2)	92.0	
	75% (H3)	95.5	
Maximum		100.0	

Finally, the performance values of minimum, hinges, and maximum were put into Equation 5.18. The rating function was deduced as follow:

$$r_{33} = \mathrm{f}(v_{33}) = \begin{cases} 0, \; v_{33} \in (0, 82.3) \\ 3.8462 * (v_{33} - 82.3), \; v_{33} \in (82.3, 88.8) \\ 25 + 7.8125 * (v_{33} - 88.8), \; v_{33} \in (88.8, 92) \\ 50 + 7.1429 * (v_{33} - 92), \; v_{33} \in (92, 95.5) \\ 75 + 5.5556 * (v_{33} - 95.5), \; v_{33} \in (95.5, 100) \end{cases} \quad .....(Eq.\ 7.13)$$

7.2.3.14 Application of rating system

Theoretically, when both SS and RC frames are proposed for a project, the decision makers might have the knowledge about the estimated performance value of attributes related to the two frames. The information can also be provided by consultants or estimated according to their work experience. The two sets of data are entered into the rating system for computation using Equations 7.1 through 7.13. In order to assist users in computing the ratings automatically, all the information that users need to enter as well as Equations 7.1 through 7.13 were included in a Microsoft Excel spreadsheet (see Appendix 5.2: Rating system)

However, in reality, decision makers might have insufficient information on the estimated performance value against every attribute for two possible reasons: designers, QS, or contractors might not have been involved in the project during its initial stage and the decision-making team might not have sufficient experience in both RC and SS projects to make the estimation. For those attributes that decision makers are unable to provide the performance value, defined ratings are given by this system.

To compute the defined ratings for RC and SS projects, the two sets of median value (30 RC projects and nine SS projects) against each attribute were entered into Equations 7.1 through 7.13. This is reasonable because the median value investigated by this study might represent the average level of those RC projects and SS projects in Singapore. The results of the defined rating of attributes are shown in Table 7.16.

Table 7.16 Defined rating of attributes

Criteria, Attribute	RC		SS	
	Performance value (Median), v	Defined rating, r	Performance value (Median), v	Defined rating, r
EC1	758.60 (S$/m^2)	54.72	1055.80 (S$/m^2)	30.05
EC2		100.00		0.00
EC3.1	10.79 (S$/m^2)	59.44	59.06 (S$/m^2)	22.16
EC5.1	2.55%	45.83	1.70%	90.00
EC5.2	4	75.00	5	100.00
EN1.1	22.93%	41.77	39.57%	93.03
EN1.3	85%	50.00	98%	92.86
EN1.5	6%	41.67	3%	78.57
EN2	24.40 (kg/m^2)	44.47	1.70 (Kg/m^2)	86.21
EN3	1143.25 (l/m^2)	36.52	0.20 (L/m^2)	99.96
CP1	1.47 (Man-day/m^2)	46.23	1.04 (Man-day/m^2)	73.38
CP2	14.01(Day/1000m^2)	48.49	11.33 (Day/1000m^2)	53.85
CP4	90.10	35.16	97.00	83.33

7.2.4 Aggregation

Once the weighting system and rating system are established, the overall score can be produced by aggregating the weighted ratings (see Equation 5.23). The formula for calculating the aggregate score of the Selection of Structural Material (SSM_k) is shown in Equations 7.14 through 7.17.

$$SSM_k = 0.485 * S1 + 0.154 * S2 + 0.361 * S3 \quad \ldots\ldots\ldots\ldots\ldots \textit{(Eq. 7.14)}$$

Where,

$$S1 = 0.313 * \begin{cases} 100, & v_{11} \in (0, 166.7) \\ 100 - 0.0987 * (v_{11} - 166.7), & v_{11} \in (166.7, 420.1) \\ 75 - 0.0599 * (v_{11} - 420.1), & v_{11} \in (420.1, 837.3) \\ 50 - 0.0913 * (v_{11} - 837.3), & v_{11} \in (837.3, 1111.1) \\ 25 - 0.0079 * (v_{11} - 1111.1), & v_{11} \in (1111.1, 4285.7) \\ 0, & v_{11} \in (4285.7, \infty) \end{cases}$$

$$+ 0.236 * \begin{cases} 100, & \text{RC frame} \\ 0, & \text{SS frame} \end{cases}$$

$$+ 0.236 * \begin{cases} 100, & v_{131} \in (0, 1.7) \\ 100 - 0.0987 * (v_{131} - 1.7), & v_{131} \in (1.7, 5.8) \\ 75 - 6.0386 * (v_{131} - 5.8), & v_{131} \in (5.8, 13.8) \\ 50 - 3.1368 * (v_{131} - 13.8), & v_{131} \in (13.8, 29.5) \\ 25 - 1.5883 * (v_{131} - 29.5), & v_{131} \in (29.5, 289.3) \\ 0, & v_{131} \in (289.3, \infty) \end{cases}$$

$$+0.214 * \left(0.512 * \begin{cases} 100, & v_{151} \in (0, 1.5) \\ 100 - 50 * (v_{151} - 1.5), & v_{151} \in (1.5, 2) \\ 75 - 50 * (v_{151} - 2), & v_{151} \in (2, 2.5) \\ 50 - 83.333 * (v_{151} - 2.5), & v_{151} \in (2.5, 2.8) \\ 25 - 20.833 * (v_{151} - 2.8), & v_{151} \in (2.8, 4) \\ 0, & v_{151} \in (4, 100) \end{cases} + 0.488 * \begin{cases} 100, & v_{152} = 5 \\ 75, & v_{152} = 4 \\ 50, & v_{152} = 3 \\ 25, & v_{152} = 2 \\ 0, & v_{152} = 1 \end{cases} \right)$$

$$\ldots\ldots \textit{(Eq. 7.15)}$$

$$S2 = 0.528 * \left(0.362 * \begin{cases} 0, & v_{211} \in (0, 18.83) \\ 3.2134 * (v_{211} - 18.83), & v_{211} \in (18.83, 19.61) \\ 25 + 5.0505 * (v_{211} - 19.61), & v_{211} \in (19.61, 24.56) \\ 50 + 6.6845 * (v_{211} - 24.56), & v_{211} \in (24.56, 28.3) \\ 75 + 1.5995 * (v_{211} - 28.3), & v_{211} \in (28.3, 43.93) \\ 100, & v_{211} \in (43.93, 100) \end{cases} \right.$$

$$+ 0.315 * \begin{cases} 0, & v_{213} \in (0, 60) \\ 1.25 * (v_{213} - 60), & v_{213} \in (60, 80) \\ 25 + 5 * (v_{213} - 80), & v_{213} \in (80, 85) \\ 50 + 3.125 * (v_{213} - 85), & v_{213} \in (85, 93) \\ 75 + 3.5714 * (v_{213} - 1111.1), & v_{213} \in (93, 100) \end{cases}$$

$$\left. + 0.323 * \begin{cases} 100 - 7.1429 * v_{215}, & v_{215} \in (0, 3.5) \\ 75 - 16.6667 * (v_{215} - 3.5), & v_{215} \in (3.5, 5) \\ 50 - 8.3333 * (v_{215} - 5), & v_{215} \in (5, 8) \\ 25 - 12.5 * (v_{215} - 10), & v_{215} \in (8, 10) \\ 0, & v_{215} \in (10, 100) \end{cases} \right)$$

$$+ 0 * \begin{cases} 100, & v_{22} \in (0, 0.1) \\ 100 - 0.0987 * (v_{22} - 0.1), & v_{22} \in (0.1, 3) \\ 75 - 8.6207 * (v_{22} - 3), & v_{22} \in (3, 13.1) \\ 50 - 0.4892 * (v_{22} - 13.1), & v_{22} \in (13.1, 64.2) \\ 25 - 0.1694 * (v_{22} - 64.2), & v_{22} \in (64.2, 211.8) \\ 0, & v_{22} \in (211.8, \infty) \end{cases}$$

$$+ 0.472 * \begin{cases} 100 - 0.1877 * v_{23}, & v_{23} \in (0, 133.2) \\ 75 - 0.0380 * (v_{23} - 133.2), & v_{23} \in (133.2, 790.8) \\ 50 - 0.0382 * (v_{23} - 790.8), & v_{23} \in (790.8, 1444.4) \\ 25 - 0.0026 * (v_{23} - 1444.4), & v_{23} \in (1444.4, 11099.3) \\ 0, & v_{23} \in (11099.3, \infty) \end{cases}$$

……*(Eq. 7.16)*

$$S3 = 0.309 * \begin{cases} 100, & v_{31} \in (0, 0.5) \\ 100 - 51.1247 * (v_{31} - 0.5), & v_{31} \in (0.5, 1) \\ 75 - 95.4198 * (v_{31} - 1), & v_{31} \in (1, 1.3) \\ 50 - 19.9362 * (v_{31} - 1.3), & v_{31} \in (1.3, 2.5) \\ 25 - 4.0115 * (v_{31} - 2.5), & v_{31} \in (2.5, 8.8) \\ 0, & v_{31} \in (8.8, \infty) \end{cases}$$

$$+ 0.353 * \begin{cases} 100, & v_{32} \in (0, 2) \\ 100 - 5.1975 * (v_{32} - 2), & v_{32} \in (2,\ 6.8) \\ 75 - 3.8521 * (v_{32} - 6.8), & v_{32} \in (6.8, 13.3) \\ 50 - 2.0046 * (v_{32} - 13.3), & v_{32} \in (13.3, 25.7) \\ 25 - 0.5659 * (v_{32} - 25.7), & v_{32} \in (25.7, 69.9) \\ 0, & v_{32} \in (69.9, \infty) \end{cases}$$

$$+0.339 * \begin{cases} 0, & v_{33} \in (0, 82.3) \\ 3.8462 * (v_{33} - 82.3), & v_{33} \in (82.3, 88.8) \\ 25 + 7.8125 * (v_{33} - 88.8), & v_{33} \in (88.8, 92) \\ 50 + 7.1429 * (v_{33} - 92), & v_{33} \in (92, 95.5) \\ 75 + 5.5556 * (v_{33} - 95.5), & v_{33} \in (95.5, 100) \end{cases}$$

……..(Eq. 7.17)

In order to assist users in calculating the aggregate scores in an automatic way, the aggregation functions were preloaded into a Microsoft Excel spreadsheet (see Appendix 5: Aggregation). After the aggregate scores are calculated, the structural frame material (RC or SS) with a higher aggregate score would indicate the most suitable option and should be selected for the building project.

7.3 Development of Decision Support System for Selection of Structural Materials (DSSSSM)

The DSSSSM developed in this study is composed of three parts—weighting system, rating system, and aggregation—provided for users in the form of three Microsoft Excel spreadsheets (see Appendix 5). The DSSSSM process is summarized in Figure 7.2. As the hierarchy tree is provided, the first step for applying this decision support system is to develop the weighting system.

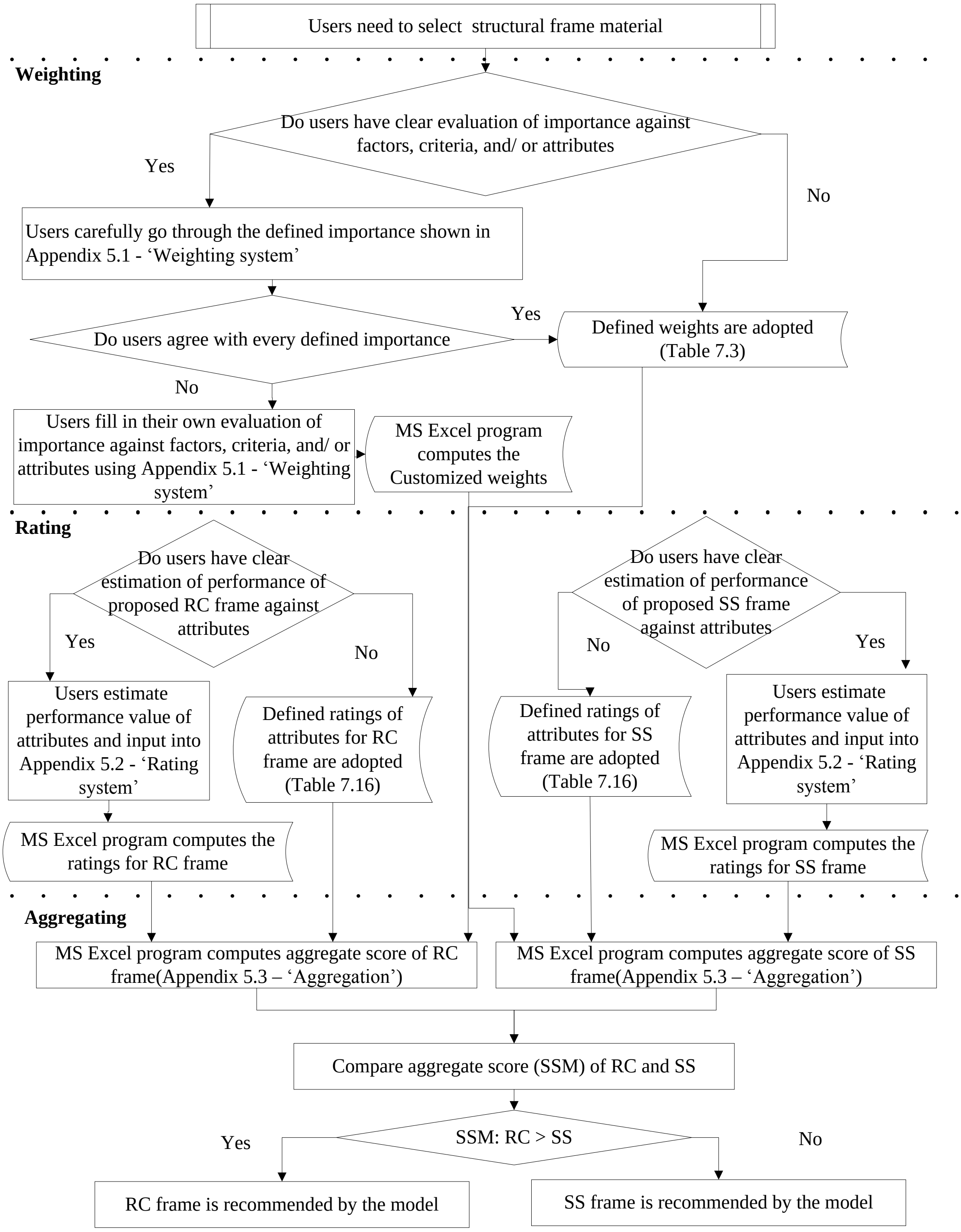


Figure 7.2 System architecture of proposed DSSSSM

The defined weighting system is adopted when users do not have a clear evaluation of importance of the hierarchy. They might jump to the next step, developing the rating system. For those users who have a clear evaluation of importance of the hierarchy, they should go through the defined importance of factors, criteria, and attributes (Q1 and Q2 in Appendix 5: Weighting system). If they agree on the defined importance, the defined weighting system is adopted to calculate the aggregate score. If they disagree, users should input their own evaluation of importance into the shaded blocks in Appendix 5.1: Weighting system. The customized weights are computed by the MS Excel program.

The next step for applying this decision support system is to develop the rating system. Users are strongly recommended to input the estimated performance value of their typical project into the shaded blocks in Appendix 5.2: Rating system. The ratings will then be provided at the right column of the same sheet. However, users may have insufficient information about the performance value of some attributes for the reasons mentioned in Section 7.2.3.14. In this situation, the defined ratings (Table 7.16) are applied for those attributes.

Having finished the previous two steps, users can find the aggregate score in Appendix 5.3: Aggregation. The structural material with a higher aggregate score as calculated by the DSSSSM is the one recommended to the users as the optimal material for structural frame.

7.4 Validation of DSSSSM

After the DSSSSM was developed, it was subjected to validation.

7.4.1 Profiles of selected experts and projects for validation

The validation exercise was conducted individually with experts who had made decision on selection structural frame between RC and SS for real projects. With the requirements described in Section 5.6, four experts had been selected for the validation exercise. The profiles of the four experts are shown in Table 7.17. The experts were selected based on convenience sampling and they fulfilled the requirements stated in Section 5.6.

Table 7.17 Profiles of the experts who conducted DSSSSM validation

Characteristics	Expert A	Expert B	Expert C	Expert D
Years in practice	17 years	20 years	23 years	25 years
Nature of experts firms	Developer	General Building contractor	Developer	Project management firm
Occupation	Project manager	General manager	Vice president	Director

Projects A, B, C, and D were individually identified by the four experts. The general information of the four projects is given in Table 7.18.

Table 7.18 Characteristics of the projects for validation

Characteristics	Project A	Project B	Project C	Project D
Project type	Complex	Residential	Factory	Residential
Height (m)	221	45	8	33
Storey	52	15	1	11
Gross Floor Area (m^2)	103,828	78,000	324	15,500
Construction cost for structural elements (S$ million)	82.5	38.1	0.5	7.8
Structural frame type	Structural Steel	Reinforced Concrete	Structural Steel	Reinforced Concrete

7.4.2 Validation process

Following the application process of DSSSSM (See Figure 7.2), experts were asked to look through the hardcopy of Appendix 5 after an introduction on how to apply the DSSSSM. Based on the decision making experience of the selected project, they were firstly asked to review the weightings of each factor, criterion and attribute. They were given the freedom to change the importance weights if they did not agree with the pre-defined importance weights offered by the DSSSSM. The second step was to rate the project against each attribute and criterion in DSSSSM. The experts were requested to write down the performance value of those measurements in shaded. After the experts finished the two sheets, the information was simultaneously input into a notebook computer which had a preloaded DSSSSM program written in Microsoft Excel (third step). The aggregate scores were computed by the Excel program and the frame with higher aggregate score was recommended at the bottom of 'Sheet - aggregation'. Then a discussion about the results and how they felt about the DSSSSM was immediately conducted.

Expert A and Expert C adopted the defined weighting system because they agreed with the pre-defined importance given in Appendix 5.1: Weighting system. Expert B chose the defined weighting system because he was not sure if his evaluation of the importance weights represented the decision making team's evaluation. Expert D chose the customized weighting system because project D was restricted by a very tight construction duration requirement. Therefore, the importance of constructability and construction duration for project D was high. Expert D also provided his own evaluation on the importance of the rest of criteria and attributes.

When going through Appendix 5.2: Rating system, the four experts were able to provide the performance information for the shaded attributes in the current structural frame. However, they had insufficient information about the estimated performance of the other alternative frame. For example, because project A was constructed of an SS frame, expert A had no knowledge about the amount of water consumption if project A were to constructed with an RC frame. Therefore, the defined ratings were applied for those attributes for which experts were not able to provide performance information. The summary of the amount of defined ratings adopted by experts is given in row 4 of Table 7.19.

After the experts finished the rating stage, the aggregate score and conclusion were given in Appendix 5: Sheet—Aggregation. The aggregate scores derived from DSSSSM for both RC and SS frames of the four projects are reported in row 5 of Table 7.19.

Table 7.19 Application of DSSSSM and consistency of DSSSSM's recommendation

Project	Project A (by expert A)		Project B (by expert B)		Project C (by expert C)		Project D (by expert D)	
Alternative frame	RC	SS	RC	SS	RC	SS	RC	SS
Weighting system used by experts	Defined weighting system		Defined weighting system		Defined weighting system		Customized weighting system	
Amount of defined rating adopted by experts	4	0	0	7	6	0	0	5
DSSSSM's aggregate score	59.74	68.05	63.76	59.06	64.23	71.69	59.96	56.8
Frame recommended by the DSSSSM		√	√			√	√	
Frame chosen in reality		√	√			√	√	
Is the DSSSSM's recommended result similar to the actual decision made?	Yes		Yes		Yes		Yes	

By comparing the frame recommended by the DSSSSM and the frame used in reality (row 6 and 7 of Table 7.19), it is concluded that the recommendations by DSSSSM for the four projects were consistent with the structural material adopted in reality. Even when the criteria weights are changed (as Expert D had done) the outcome showed that the model's recommendation result was similar to the actual decision made.

7.4.3 Actual decision making process of experts

The experts were asked to describe how and why they choose the current frames. All four experts expressed that they did not have a systematic model to assist them in selecting the structural frame. Their decisions were based on only two or three factors and a simple comparison of the performance of those factors. The descriptions from the four experts are provided below.

Expert A: Project A is a complex building mixed of a shopping mall and hotel. We wanted this building to be operated as early as possible so that we might have our money back earlier. We do not have a model to help us to select the structural frame. The SS frame was chosen because it could save us more than half a year and about S$200/m^2 additional cost was acceptable for us.

Expert B: The client had proposed an SS frame because the government encourages high-productivity construction method. However, we found out that using SS might increase the costs about S$15 million after we consulted with contractors and QS. This went well beyond the clients' expectation and, therefore, they chose the frame.

Expert C: We chose the SS frame for this project for three reasons. First, about 20% of SS elements of this project used recycled materials taken from another factory of ours. Second, the construction of SS frame, especially for a factory, is very fast. This structural frame was completed within only half a month. Finally, using the SS frame for this project was actually cheaper than using an RC frame because of the use of recycled materials.

Expert D: We were thinking about using an SS frame because the client had a strict requirement about the construction duration. We asked QS and contractors to provide an estimation of the construction duration and costs of using RC frame and SS frame. Finally, we found out that using SS could save us only one month with an additional S$3 million in costs. The time savings was not cost-efficient and, therefore, we chose the RC frame.

As indicated, the decision-making processes involved in the four projects are similar. First, decision makers paid attention to only two or three factors that they thought were important, such as construction speed, labor efficiency, and costs. Then they investigated the performance of those factors by consulting with experts. Finally, they made their decisions based on the comparative result. They admitted that their decision making process was not scientific and needed to be improved by integrally considering the economic performance, environmental performance, and constructible performance. They felt that the DSSSSM developed in this study was able to meet this demand.

7.4.4 *Experts' comments on the DSSSSM*

This section reports the four experts' perspectives of the DSSSSM and their views of the practicality of the system.

During the interviews in the validation stage, the four experts developed a understanding of the DSSSSM by completing the sheets in Appendix 5. Once they saw the results derived from the DSSSSM, they were asked to comment on the decision hierarchy tree, the weighting system, the rating system, the aggregate scores, and the application process of the DSSSSM.

The four experts observed that the DSSSSM could not only simulate the real decision process, but also provide a systematic decision tree and a scientific method to help decision makers select a structural frame.

They agreed that the system had identified the decision hierarchy tree, which is necessary for the evaluation of structural materials. None of them proposed additional attributes to be used to evaluate structural material. Therefore, it was concluded the decision hierarchy tree was complete. Expert A explained that:

> *This system provided a series of systematic criteria for such decision making. It will help us select the structural material in a more scientific way. When we decided the structural frame material for this project, we only considered two factors: cost and construction speed. It was not thoughtful enough for such a decision process because we missed some important factors which have been addressed in your study.*

In terms of the weighting system, the four experts agreed that the defined importance of factors, criteria and attributes are appropriate for evaluating structural materials in a general sense. Three of them pointed out that the

DSSSSM was great because it provides a customized weighting system that enables users to develop their own weights for projects with typical restrictions. Expert C explained that:

> *The defined weights may represent our views on the importance of these criteria. Those weights are suitable for normal projects. One of the advantages of the DSSSSM is that it allows users to input their own ratings of the importance of those criteria which the decision team focuses much more upon.*

The four experts stated that the two sets of performance values used to compute defined ratings for RC and SS frames generally reflected the performance of the two frames in Singapore. All of the experts mentioned that the defined performance values and corresponding defined ratings were useful for decision makers, especially when a project was in its early stage. Expert B explained that:

> *The defined performance values and ratings given by the DSSSSM are reasonable to me. These defined performance values are very helpful for a management team. For example, we may have an overview of the performance of proposed frames without consulting with contractors or consultants in the very early stage. And we may know how far away we are from the average level in the industry.*
>
> *This DSSSSM is good because of its flexibility to users. In the design stage, we have more detailed information of the project so that we are able to estimate the performance of some criteria. This DSSSSM is flexible for us as it allows us to replace the defined performance values of these criteria with our own estimated values. As a result, the ratings will be more reliable if we use our estimated performance values of the proposed frames.*

The four experts agreed with the aggregate scores given by the DSSSSM and noted that the frames recommended by the DSSSSM were the same as their real decisions regardless of whether they chose the defined weighting system or customized weighting system.

All of the experts held similar views on the practicality of the DSSSSM. They said this system was helpful and convenient to use not only for users with limited experience, but also for users with extensive experience, like them. They stated that they would use the DSSSSM if it were available to them.

7.5 Summary

This chapter addresses objective 4 of the study, which is to develop and test a decision support system for selection of structural frame material to achieve optimal economic sustainability, environmental sustainability, and constructability. The decision support system for the selection of structural material (DSSSSM) was developed. This system comprised a weighting system, rating system, and aggregation component.

In the DSSSSM, both defined weighting system and customized weighting system were available for users. The defined weighting system was developed based on the mean importance of the factors, criteria and attributes as indicated by survey respondents (see section 7.2.2.1). For those users who desire to indicate their own importance weights, the DSSSSM software (see Appendix 5.1) had been preloaded with the necessary equations to enable customized weighting system to be implemented. The rating system was developed based on the performance data of the 39 projects investigated in this study (see section 7.2.3). When deciding between which structural frame material to use, users are to enter the estimated performance value of each attribute or criterion for the project. If users could not provide the estimated performance value of any attribute, they may use the pre-defined ratings embedded in the DSSSSM software.

The equations used to compute the aggregate score of DSSSSM are given in Equations 7.14 through 7.17. The structural frame with the higher aggregate score is the better one and is recommended for adoption. The DSSSSM is provided in MS Excel program (Appendix 5).

The DSSSSM was validated by collecting four sets of new project data comprising 2 RC-framed and 2 SS-framed buildings. The results from the validation showed that the DSSSSM was robust as its predictions were similar to experts' actual decisions. According to the experts interviewed at the validation stage, the DSSSSM is appropriate for evaluating structural frame materials and is helpful for practical use.

CHAPTER 8 SUMMARY AND CONCLUSION

8.1 Summary

The role played by the construction industry is a significant one. It not only contributes to national development and affects economic growth. Its activities also have an impact on the environment. Due to an increased awareness of sustainable development, the construction industry is now presented with the challenges of reducing material consumption, energy consumption and CO_2 emission, as well as other environmental issues. In addition, the Singapore government has launched a constructability appraisal system and a productivity enhancement scheme to encourage the construction industry to improve constructability. One of the goals of many business concern has always been to raise profitability. However, with the added pressure to reduce the environmental impact of business activities, economic gains should no longer be the only driving factor behind the decision making of an enterprise. Herein lies the challenge to achieve the right balance among environmental performance, constructibility performance and economic performance. There is a clear need to establish the connection between these three aspects.

The aim of this study is to investigate and compare the economic sustainability, environmental sustainability and constructability performance of the structural steel (SS) frame and reinforced concrete (RC) frame in Singapore, and to develop and test a decision support system that will aid the selection of structural frame material to achieve optimal economic sustainability, environmental sustainability and constructability (see Section 1.4). To establish such a system, a holistic framework is built to show the factors that affect decision making when the structural structural frame material of a building is being selected (see Section 4.6). The framework is underpinned by the theory of the firm (see Section 4.2.1), the rational choice theory (see Section 4.2.2) and the CSR theory (see Section 4.3.1) as well as the concepts of sustainability (see Section 4.3.2) and constructability (see Section 4.4).

The choice of research method for this study is the survey. This is because survey is suitable for the type of research question “what” (such as, what factors affect selection of structural frame materials), “how much” (such as, how much to construct the structure elements of a RC-framed building) and “how many” (such as, how many manpower had been consumed to construct the structure elements of a SS-framed building). The data was collected through face-to-face interviews using a structured questionnaire (see Appendix 2 and3). In total, 39 completed questionnaires were gathered from experts with extensive experience in the selection of structural frame materials. From the statistical analysis, the comparative result between SS and RC were drawn based on the three categories of economic performance, environmental performance and constructability performance.

A conceptual framework was developed after reviewing on the concepts and implications of sustainability and constructability. Based on the conceptual framework (see Figure4.2), the decision hierarchy tree was refined by removing those criteria and attributes which had similar performance or been identified as non-important in the selection of structural material (see Figure6.1). The decision support system (DSSSSM) was established using the multi-attribute value technique (see Section 6.2). To make the DSSSSM helpful for users who do not have a deep knowledge of alternative structural frames, this study offers a defined weighting system and defined ratings based on the survey results. Users input the information of those attributes of which they have the estimated performance value. Defined weights are employed when users are not sure about their own priorities, and defined ratings are adopted for those attributes whose performance value users are unable to provide. In order to validate this system, the information on two RC projects and two SS projects were fed into this system to check whether the frame recommended by the DSSSSM was consistent with real choice. The results showed that this system is robust and practical for real use (see Section 7.4).

8.2 Findings and validation of hypothesis

Objective 1 was to study the economic sustainability, environmental sustainability and constructability performance of RC-framed buildings (see

Section 1.4). Thirty RC-framed projects were investigated. The measurements of performance of economic sustainability, environmental sustainability and constructability are found in sections 6.4, 6.5, and 6.6 respectively. These are summarized in the second column of Table 8.1. The maximum value, the minimum value and the median value of each criterion and attribute are also reported in Table 8.1. (See section 6.4 to 6.6 for details.).

Table 8.1 Performance of RC-framed buildings

Parameters	**Measurements**	**Performance of RC frame**		
		Minimum	Maximum	Median
Economical sustainability(EC)				
Structural cost (EC1)	Unit structural cost (S$/$m^2$)	166.70	1,823.60	758.60
Maintenance cost (EC2)	Total maintenance cost / Total GFA (S$/$m^2$)	0	0	0
Non-construction cost (EC3)				
Financial costs (EC3.1)	Unit cost (S$/$m^2$)	1.69	33.74	10.79
Additional incomes (EC5)				
Additional usable area (EC5.1)	Sectional area of columns / Floor area of a standard level (%)	2	4	2
Flexibility of utilizing internal area (EC5.2)	1 = “extremely unsatisfactory” 2 = “unsatisfactory” 3 = “neutral” 4 = “good” 5 = “outstanding”	2	5	4
Environmental sustainability(EN)				
Material consumption (EN1)				
Recycling rate (EN1.1)	Percentage of recycled steel	12	28	23

Parameters	**Measurements**	**Performance of RC frame**		
		Minimum	Maximum	Median
	being used for structural elements (%)			
Recyclability (EN1.3)	Proportion of recyclable structural material in the end of life stage (%)	60	98	85
Waste rate (EN1.5)	Percentage of wasted material against total material consumption (%)	3	10	6
CO_2 emission (EN2)	CO_2 emission / Total GFA (kg/m^2)	0.80	211.80	24.40
Water consumption (EN3)	Water consumption / Total GFA (l/m^2)	133.20	11088.30	1143.25
Noise	1 = "extremely unsatisfactory" 2 = "unsatisfactory" 3 = "neutral" 4 = "good" 5 = "outstanding"	2	5	3
Constructability Performance (CP)				
Labor consumption (CP1)	Amount of labor consumption / Total GFA (Man-day/m^2)	0.78	8.77	1.47
Construction duration (CP2)	Duration of structural construction *1000/Total GFA (Day/1000m^2)	1.95	69.89	14.01
Construction safety (CP3)	Accident Severity Rate (ASR)	0	464	182
Construction quality (CP4)	CONQUAS score	82	100	90

Objective 2 was to investigate the economic sustainability, environmental sustainability and constructability performance of SS-framed buildings (see Section 1.4). Nine SS-framed projects were studied. The same measurement criteria for RC-framed buildings were used to measure the performance of economic sustainability, environmental sustainability and constructability of SS-framed buildings. The performance values of the SS frame, including the minimum value, maximum value and median value, are shown in sections 6.4, 6.5 and 6.6 respectively, and summarized in Table 8.2.

Table 8.2 Performance of SS-framed buildings

Parameters	**Measurements**	**Performance of SS frame**		
		Minimum	Maximum	Median
Economical sustainability(EC)				
Structural cost (EC1)	Unit structural cost (S$/m^2)	375.00	4,285.70	1055.80
Maintenance cost (EC2)	Total maintenance cost / Total GFA (S$/m^2)	34.60	328.10	221.70
Non-construction cost (EC3)				
Financial costs (EC3.1)	Unit cost (S$/m^2)	14.74	289.29	59.06
Additional incomes (EC5)				
Additional usable area (EC5.1)	Sectional area of columns / Floor area of a standard level (%)	1	2	2
Flexibility of utilizing internal area (EC5.2)	1 = “extremely unsatisfactory” 2 = “unsatisfactory” 3 = “neutral” 4 = “good” 5 = “outstanding”	4	5	5
Environmental sustainability (EN)				
Material consumption (EN1)				
Recycling rate (EN1.1)	Percentage of recycled steel being used for structural elements (%)	38	44	40

Parameters	Measurements	Performance of SS frame		
		Minimum	Maximum	Median
Recyclability (EN1.3)	Proportion of recyclable structural material in the end of life stage (%)	90	100	98
Waste rate (EN1.5)	Percentage of wasted material against total material consumption (%)	0	5	3.00
CO_2 emission (EN2)	CO_2 emission / Total GFA (kg/m^2)	0.10	91.00	1.70
Water consumption (EN3)	Water consumption / Total GFA (l/m^2)	0.00	7.10	0.20
Noise (EN4)	1 = "extremely unsatisfactory" 2 = "unsatisfactory" 3 = "neutral" 4 = "good" 5 = "outstanding"	1	4	3
Constructability Performance (CP)				
Labor consumption (CP1)	Amount of labor consumption / Total GFA (Man-day/m^2)	0.53	1.94	1.04
Construction duration (CP2)	Duration of structural construction *1000/Total GFA (Day/1000m^2)	5.00	25.71	11.33
Construction safety (CP3)	Accident Severity Rate (ASR)	0	328	147
Construction quality (CP4)	CONQUAS score	90	98	97

Objective 3 was to compare the economic sustainability, environmental sustainability and constructability performance of structural frames using two different materials (see Section 1.4). The comparative result between SS and RC are summarized as follows:

- Economic performance: SS projects incur significantly higher structural costs (EC1), maintenance costs (EC2) and non-construction costs (EC3), but provide significantly higher additional incomes (EC5) than RC projects (see Section 6.4);

- Environmental performance: SS projects have significantly less material consumption (EN1), CO_2 emission (EN2) and water consumption (EN3) than RC projects. The two frames exhibit similar extent of noise (EN4) during construction (see Section 6.5); and

- Constructability performance: SS projects have significantly more labor saving (CP1), higher construction speed (CP2) and better construction quality (CP4) than RC projects. Construction safety (CP3) performance is similar for both frames (see Section 6.6).

Objective 4 was to develop and test a decision support system that will aid the selection of structural frame material to achieve optimal economic sustainability, environmental sustainability and constructability (see Section 1.4). A decision support system, DSSSSM, was established using the MAVT (see Section 5.5). The framework of this DSSSSM was proposed based on a literature review on economic sustainability, environmental sustainability and constructability. A series of questionnaires were then developed to investigate the importance and performance of each criterion and attribute of the framework.

The DSSSSM was constituted by a weighting system (see Section 7.2.2), rating system (Section 7.2.3) and aggregation (Section 7.2.4). This is given in three MS Excel spreadsheets with preloaded input information tables and calculation formula (see Appendix 5).

Two weighting systems and defined ratings were provided for users (see Section 7.2.2). This made the DSSSSM not only helpful for users who have sufficient experience in the construction industry, but also flexible for users who do not have a deep knowledge of alternative structural frames. The DSSSSM assists users who have sufficient experience in the construction industry by providing a systemic decision tree and a scientific computation process. Users key in their priorities against the listed attributes, criteria and factors in the customized weighing system and then input the estimated performance value of alternatives into the rating system (see Section 7.2.3.14). Finally, the frame with the higher aggregate score will be recommended to users by the DSSSSM (see Section 7.2.4).

To test the DSSSSM, the information on two RC projects and two SS projects were fed into this DSSSSM. It was found that the structural frame material recommended by the DSSSSM was consistent with decision that experts have made in reality (see Section 7.4.3). The comments from the four experts indicated that the DSSSSM provided a more systemic and scientific basis for decision making than their actual decision making processes and they would be willing to use this DSSSSM if it is made available to them.

The hypothesis proposed in Section 4.5 and the test results are presented and reviewed below.

Hypothesis 1- Decision making on structural material selection is affected by the material's performance in economic sustainability, environmental sustainability and constructability.

The survey results supported this hypothesis. All of respondents agreed that all the three factors affect the decision making on structural frame material selection (see Section 6.3.1).

Hypothesis 2 - Economic performance (EC) associated with structural materials is affected by structural costs (EC1), maintenance costs (EC2), non-construction costs (EC3), end of life costs (EC4) and additional incomes (EC5).

- H2.1 – RC frame has lower structural costs than SS frame
- H2.2 – RC frame has lower maintenance costs than SS frame
- H2.3 – RC frame has lower financial costs than SS frame

- H2.4 – RC frame has higher end of life costs than SS frame

- H2.5 – RC frame has lower additional income than SS frame.

Hypothesis 2 was partly supported. The survey results showed that structural costs (EC1), maintenance costs (EC2), non-construction costs (EC3), and additional incomes (EC5) significantly affect the decision making on structural material selection. However, according to the survey, the end of life cost (EC4) was not significantly important in the selection of structural material. Corporate tax (EC3.2), an attribute under EC3, and possible incentive from BCA (EC5.3) under EC5, were identified as not significantly important in the selection of structural material (see Section 6.3.2).

According to the investigation on economic performance, H2.1, H2.2, H2.3 and H2.5 were supported (see Section 6.7.2).

Hypothesis 3 - Environmental performance (EN) associated with structural materials is affected by material consumption (EN1), CO_2 emission (EN2), water consumption (EN3) and noise (EN4).

- H3.1 - RC frame has higher material consumption than SS frame

- H3.2 - RC frame has higher CO_2 emission during construction than SS frame

- H3.3 - RC frame has higher water consumption than SS frame during construction

- H3.4 - RC frame produces more noise than SS frame during construction.

Hypothesis 3 was supported to various degrees. The survey results showed that material consumption (EN1), water consumption (EN3) and noise (EN4) affect the decision making on structural material selection. It should be highlighted here that CO_2 emission (EN2) will become an important factor in the near future although it was not significantly important in the selection of structural material in those projects that were investigated in this study (see

Section 6.3.2). Two attributes – the reuse rate of structural material (EN1.2) and the reusability of structural material (EN1.4) – under material consumption (EN1) were identified as non-important in the selection of structural material. The reasons and discussion are found in Section 6.7.1.

According to the investigation on environmental performance, H3.1, H3.2, and H3.3 were supported (see Section 6.7.3). H3.4 is not supported as it was found that RC-framed projects and SS- framed projects produce noise to a similar extent.

Hypothesis 4: Constructability performance (CP) associated with structural materials is affected by labor saving (CP1), construction speed (CP2), construction safety (CP3) and construction quality (CP4).

- H4.1 - SS frame requires less labor than RC frame
- H4.2 - SS frame has faster construction speed than RC frame
- H4.3 - SS frame is safer to construct than RC frame
- H4.4 - SS frame has higher construction quality than RC frame.

Hypothesis 4 was fully supported. The survey results showed that all the four criteria – labor saving (CP1), construction speed (CP2), construction safety (CP3) and construction quality (CP4) – affect the decision making on the selection of structural material (see Section 6.3.2).

According to the investigation on constructability performance, H4.1, H4.2 and H4.4 were supported (see Section 6.7.4). H4.3 was not supported as it was found that RC-framed projects and SS-framed projects showed similar construction safety performance.

8.3 Contribution to theory and knowledge

This study contributes to knowledge in several ways.

First, this study introduced a theoretical framework for structural material selection based on the integration of economic sustainability, environmental sustainability and constructability concepts. This integration is an improvement of previous models. For example, Castro-Lacouture's (2008) model and Paya-Zaforteza's (2009) model integrated environmental goals and budget requirements when selecting building materials; Elnimeiri and Gupta's (2008) model considered environmental goals and constructability when undertaking structural design; and Sirisalee's (2004) model provided guidance on how to minimize thickness, mass of casting and cost of structural materials. It can be seen that these previous models are not comprehensive as they only considered one or two factors. This study improves those models by integrating three important factors.

Second, the DSSSSM provides a good example of how economic goals, environmental constraints and constructible targets can be balanced when selecting structural frame material. This study also provides a theoretical basis for the pursuit of better sustainability and constructability performance in construction.

Finally, it was found that a limitation of the theory of the firm (Archibald, 1987; Panzar & Willig, 1981) and the rational choice theory (Becker, 1978) are not able to model the decision behaviour of a firm when selecting structural frame materials. This study contributed to knowledge by showing that the two theories should be considered by firms in conjunction with other concepts or issues such as environmental sustainability and constructability concept when selecting structural frame materials.

8.4 Contribution to practice

One of the current problems in the construction industry is the lack of a system to guide developers and consultants in making appropriate decisions in the selection of key elements of the product, such as in selecting the material for structural frame of a building. This study contributes to the practice by developing a decision support system (DSSSSM) to assist developers and consultants in their decision making to select structural frame materials. It also provides automates the decision using Excel (see Appendix 5). In addition, the DSSSSM helps the industry to select the structural frame material in a more scientific and sustainable way. In the design process, the DSSSSM may be used in the concept design stage to guide the preliminary design. It may also used in the stage of preliminary design. As a feedback, the result of DSSSSM might affect the concept design (refer to Figure 8.1).

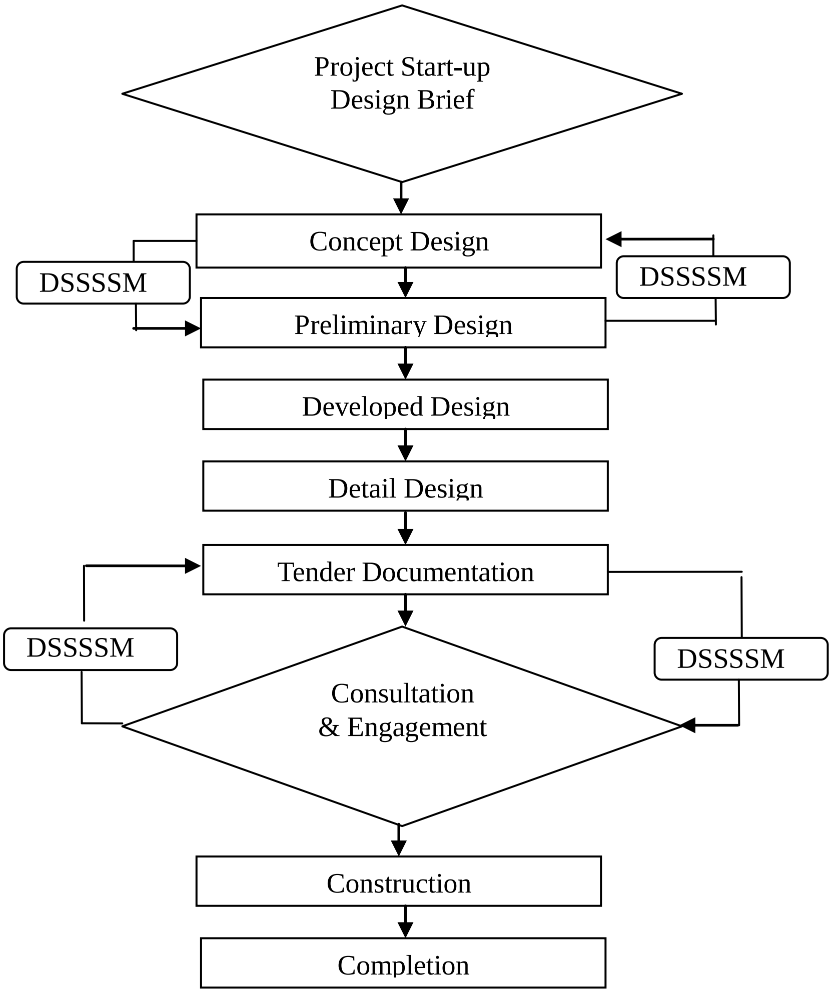


Figure 8.1 The application of DSSSSM in design process

The DSSSSM provides a decision hierarchy tree which enables users to have a more systemic consideration when selecting the structural material. This can change the approach businesses adopt in other areas as well from single considerations to multi-criteria decision making.

Furthermore, the DSSSSM provides the defined weights and defined performance values which are useful references for developers and consultants when they prepare tender documentation. If the rating of a certain attribute or criterion is lower than the defined rating, it indicates that the performance of the alternative is lower than the average level, and therefore improvements should be made. The defined weights and defined performance values provided by this study will be especially helpful for users without much experience in the construction industry as it will give them a good understanding of the performance of RC-framed buildings and SS-framed buildings.

In addition, this study contributes to practice by providing the comparative results in terms of economic performance and labor efficiency in the construction of SS-framed buildings and RC-framed buildings. This may enable the Singapore government to have a better understanding of the additional costs, benefits and labor saving involved in using SS frames and RC frames. With this, the government can work towards improving the incentive schemes in a more effective way if it intends to encourage the industry to choose the frame with better performance and greater labor efficiency. The BCA may improve its Construction Productivity and Capability Fund (CPCF) by adjusting its incentive schemes to provide stronger support to the industry in raising productivity and building up capabilities.

8.5 Recommendation for practice

Developers and consultants should use the DSSSSM developed in this study to assist them in the selection of a structural frame system. The DSSSSM can also be used by developers and consultants to assess alternative structural frames. The DSSSSM allows users to know the suitable frame which is likely to achieve optimal outcome after balancing economic performance, environmental performance and constructible performance.

The Singapore Green Mark Scheme (V4.1) (BCA, 2013) has an item referred to as “sustainable construction” which constitutes 10 points. The current evaluation method is based only on the use of sustainable and recycled material (the current version has only two recycled materials: green cement and recycled concrete aggregate) and the concrete usage index. BCA should consider other criteria identified in this study for assessing Green Mark’s “sustainable construction”. These include: recycling rate, recyclability, CO_2 emission during construction, water consumption during construction and noise pollution during construction as this study has shown that these are relevant and significant measures under sustainable construction (see Section 6.7.1). The survey results of the performance against these criteria are also useful for further developing the benchmark to evaluate these criteria.

The Singapore Green Labelling Scheme (SGLS) currently has only three materials under the category of building materials (SEC, 2013). They are cement and precast concrete products, brick and tile/ceramics. SGLS can introduce SS and RC into the building materials category. SGLS may refer to the CO_2 emission calculation method and the emission results of constructing SS buildings and RC buildings developed in this study (see Section 6.5.2).

8.6 Limitations of the research

One limitation of this research is the small sample size due to the low response rate. There are three likely reasons for the low response rate. First, in order to ensure that the information for investigation is reliable, the data for each project had to be obtained from contractors, consultants and clients. It was not easy to involve all the three different stakeholders in this investigation. Second, some contractors refused to answer questions such as those on structural costs as they considered the information confidential. Third, owing to a lack of practice of record keeping, some key data (such as water and electricity consumption) were not readily available, and respondents would have had to go through previous documents. Some incomplete questionnaires have been received because some contractors were not willing to spend much time going through previous documents. After excluding all the incomplete questionnaires, complete information on only 30 RC buildings and nine SS buildings were obtained even though the data collection had taken one whole year. In order to overcome the problems of low response rate, up to three reminder telephone calls were made to those contractors who stated that they needed to check project documents to answer some questions after the interview.

Admittedly, the 30 projects cannot fully represent the many RC-framed buildings that were completed between 2009 and 2011. Notwithstanding this, the findings should still be considered to be valid because according to central limit theorem, the samples will be approximately normally distributed when sample size is not less than 30 (Rice, 1995).

In Singapore, there is no official record of all existing and ongoing SS-framed projects. In order to obtain information on the whole population of SS-framed building, all 188 licensed SS contractors were contacted to find out if they had constructed SS-framed buildings before. Of the 188, seven said that they had, and questionnaires were sent to all seven of them. Excluding three uncompleted questionnaires, the sample size of SS-framed buildings in this study was only nine. As a result, the performance values of SS projects had large variability. Because of the small population of SS-framed projects in Singapore, even though data of only nine SS-framed projects were collected, this was useful to inform the research.

The second limitation of this study is that it did not consider other factors such as project type and project complexity because of the small total number of project data collected. Taking project type as an example, there were 17 residential RC-framed projects and no residential SS-framed projects making it impossible to compare these 2 building types. However, this limitation is not expected to affect the results significantly as other studies (for example(Alnaser & Flanagan, 2007; Chan & Chan, 2004; Chen et al., 2001; Gangolells et al., 2009)) have also included different project types within the same sample for analysis.

The third limitation of this study is that the weights of the attributes in the DSSSSM were calculated based on the respondents' perception of the level of importance of these attributes on a 1-9 AHP scale (for factors) and a 1-5 Likert scale (for criterion and attributes) (see sections 5.5.2). The weights derived from the two methods may not be totally reliable because the rating processes were based on the subjective evaluation of the respondents. However, steps were taken to minimize this by providing a suitable description to anchor each rating.

The fourth limitation of this study is that the disruption in the supply of sand and aggregates to Singapore in 2007 had not been considered. It was reported by Singapore Department of Statistics that the price of sand and aggregate tripled in March of 2007 and the prices stabilized towards the later part of 2007 (Statlink, 2010). This disruption had major impacts on the construction industry in Singapore, especially for projects using concrete. This impact had been minimized by investigating only those RC projects completed during 2009 to 2011. Admittedly, some of these projects were ongoing in 2007, and inevitably sand and aggregates were bought in March of 2007. However, the results of this study are still reliable because the large increase in prices of sand and aggregates had occurred for only one month and the proportion of sand and aggregates bought at high prices is likely to be small for those RC projects with more than three years construction duration.

8.7 Conclusion

RC and SS are the two main structural frames used in building projects in Singapore. To stand up to the pressure of sustainable development and national productivity improvement, the Singapore construction industry needs to adopt structural frame materials which will optimize economic performance, minimize environmental impact and maximize constructability and productivity. To do so, it is vital for the industry to be informed on what should be considered when selecting the structural frame material, how the two frames perform in terms of economic, environmental and constructability performance, and how to evaluate the structural frame material. Information on these three aspects will also be invaluable to the government to help it develop more effective incentive schemes and legislation to encourage the construction industry to develop in a more sustainable and constructible manner.

In order to achieve sustainable and constructible construction, it is essential for firms in construction industry to integrally consider economic sustainability (including structural costs, maintenance costs, non-construction costs and additional incomes), environmental sustainability (including material consumption, CO_2 emission and water consumption) and constructability (including labor saving, construction duration and construction quality) should be systematically considered when selecting the structural material.

If the Singapore government want to encourage the construction industry to adopt the more environmental friendly structural frame material (SS) to match with the national sustainable development strategy, the government should provide proper incentive and disseminating the advantages of SS frame such as higher labor-efficiency, higher construction quality and faster construction speed. This is because SS-framed buildings currently have better performance in environmental sustainability and constructability than RC buildings but suffer from higher costs, firms might prefer to use RC frame if they extremely focus on the costs.

In conclusion, firms from construction industry should adopt scientific and appropriate multi attributes decision making approach identified by this study to enhance their competitiveness by providing sustainable and constructible construction.

8.8 Recommendations for future studies

Following this study, some areas of research are suggested for future studies.

First, the decision hierarchy tree of the DSSSSM was developed based on economic theories, the sustainability concept, and the constructability concept. Because these theories and concepts continue to evolve, the decision hierarchy tree of the DSSSSM could be expanded by incorporating additional criteria (such as social sustainability) if more implications from these theories and concepts are examined and determined to be applicable in the future.

Second, this study has taken the first step in building a decision support system for the selection of structural frame materials. In order to ensure that the DSSSSM remains helpful for future use, the weights and rates of the DSSSSM should be kept updated. It is recommended that this updating be conducted based on a continuous investigation of the economic performance, environmental performance and constructability performance of SS-framed buildings and RC-framed buildings with a larger sample size.

Third, the DSSSSM is for all project types. This study was not able to consider project type due to the small number of SS buildings. It is recommended for the future studies that investigation and comparison between RC buildings and SS buildings based on a typical building type should be conducted. Then the DSSSSM might be further improved by developing separate sub interfaces based upon different project types (such as one interface for residential buildings, another interface for commercial buildings).

Fourth, the DSSSSM is suitable for the selection of structural frame materials from the following two options: SS frame and RC frame. It is not applicable when other options – for example, a hybrid system such as RC frame mixed with SS frame – need to be considered. It can be seen there is a trend for building design towards higher and more complex. Therefore, more hybrid structures will appeared in the future, and then hybrid system should be included as the third option for further development of the DSSSSM.

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Appendix 1: Questionnaire for RC contractors

Letter to participants

National University of Singapore, Department of Building

Interview on Decision Support System for Selection of Structural Frame Material to Achieve Sustainability

Dear Sir/Madam,

I am conducting a research to study the selection of optimal structural frame material for building projects in Singapore. This study involves a survey and your participation is very much needed and appreciated because of your deep knowledge in economic performance, environmental sustainability, and constructability performance of buildings.

I would be grateful if you could grant me a one hour interview. The purposes are to seek your advice on RC framed building which was completed within the past 3 years.

There is no commercial interest involved in this study. All information we obtain will be treated as confidential and used solely for the purpose of research.

If you would like a summary of the research findings, this can be made available to you. If you have any queries, please do not hesitate to contact me at Tel No: 90271876 or email to g0700345@nus.edu.sg .

I am grateful for your co-operation and hope to hear from you.

Thank you very much for your help.

Your sincerely

Zhong Yun

Ph.D. Candidate

Instructions: Please answer the questions by putting a “√” or filling in the blanks.

Part A: General information

1. Your name (Optional):___________________.

2. Company Name (Optional):_________________.

3. Work experience (please tick one):

[ ] Developer; [ ] Main contractor; [ ] Subcontractor;

[ ] Consultant (architect); [ ] Consultant (structural engineer);

[ ] Consultant (project management); [ ] Structural steel fabricator;

[ ] Quantity surveyor; [ ] Other, please specify____.

4. Years of work experience in construction industry: _____ years.

5. How many RC-framed projects have you been involved in: _______;

6. How many structural steel projects have you been involved in: _______;

Part B: Information on RC-framed building

Instructions: Please answer the questions based on a completed steel-framed building project that you have been involved in.

7. Project name:_______________________.

Construction completed in (year)________.

8. Type of project: [ ] Residential; [ ] Commercial; [ ] Hotel; [ ] Institute; [ ] Factory or entertainment; [ ] Mixed; [ ] Other, please specify ____.

9. Gross floor area (GFA) of the whole project: ________m^2.

10. Height of building: ______m (excluding basement);____stories (excluding basement); ____stories (basement).

11. Construction duration for the project: from___ (yyyy/mm) to___(yyyy/mm);

Construction duration for the foundation: from___(yyyy/mm) to___(yyyy/mm);

Construction duration for the structural frame: from_________(yyyy/mm) to (yyyy/mm).

12. Contract sum for the whole project: S$____; Contract sum for the structural frame: S$___.

13. Costs of structural materials:

Material amount (including beams, columns and slabs)	RC frame	
	Reinforcement bars (ton)	Concrete (m^3)
Basement		
Super-structure		

Steel Price: S$_____/ton Ready mix concrete price: S$_____/ m^3

Steel imported from: __ton from China; __ton from___ (country name).

14. Foundation type: (e.g., bored piles, RC piles): please specify .

Cost of foundation: S$_____.

Amount of excavation: _____ m^3; Cost of excavation: S$___.

15. Total manpower for structural construction (including form work, rebar installation, concrete casting, and so on.): ____ (man day/man hour).

Number of staff (supervisor level above): ___.

16. Does this frame require any maintenance during operation stage after turning over?

[ ] Yes; [ ] No.

If yes, please estimate the cost for maintenance S$_____.

17. Costs of machinery:

Machinery		Rental (S$/month)	Duration (month)	
			For whole project	For structural frame
Crane1 (ton)				
Crane2 (ton)				
Tower crane (__m* capacity__)				
Rebar cutting				
Bumping				
Air compressor				
Other (please state)				
Total				

18. Contingency cost (if any): S$______.

19. Amount of reused structural RC elements for this project:_____%.

20. Amount of recycled concrete for this project:_____m^3.

21. The waste rate of steel (on-site construction and prefabricator factory): ___%; the waste rate of concrete (on-site construction):__%;

22. Energy consumption of the project:

Energy consumption	Diesel consumption (l)	Electricity from power grid (kwh)	Gasoline (l)
Total energy consumption for all construction processes (including the architectural stage)			
Energy consumption for structural construction (please estimate the amount or the percentage of the total)			

Accommodation of laborers: [ ] on site; [ ] not on site

23. The extent of noise produced during the structural frame construction processes:

[ ] extremely unsatisfactory [ ] unsatisfactory [ ] neutral [ ] good [ ] outstanding

24. Water consumption during the structural frame construction processes: ___________m^3.

25. Accident Severity Rate (ASR) of this project:______.

26. The CONQUAS score (structural) achieved by this project:___ .

End of survey.

Thank you for your participation in responding to this questionnaire.

All information will be kept strictly confidential.

If you have any queries, please do not hesitate to contact Ms. Zhong Yun at 90271876 or email me at g0700345@nus.edu.sg

Appendix 2: Questionnaire for SS contractors

Letter to participants

National University of Singapore, Department of Building

Interview on Decision Support System for Selection of Structural Frame Material to Achieve Sustainability

Dear Sir/Madam,

I am conducting a research to study the selection of optimal structural frame material for building projects in Singapore. This study involves a survey and your participation is very much needed and appreciated because of your deep knowledge in economic performance, environmental sustainability, and constructability performance of buildings.

I would be grateful if you could grant me a one hour interview. The purposes are to seek your advice on a steel framed building which was completed within the past 10 years.

There is no commercial interest involved in this study. All information we obtain will be treated as confidential and used solely for the purpose of research.

If you would like a summary of the research findings, this can be made available to you. If you have any queries, please do not hesitate to contact me at Tel No: 90271876 or email to g0700345@nus.edu.sg .

I am grateful for your co-operation and hope to hear from you.

Thank you very much for your help.

Your sincerely

Zhong Yun

Ph.D. Candidate

Instruction: Please answer the questions by putting a "√" or filling in the blanks.

Part A: General information

1. Your name (Optional):___________________.
2. Company Name (Optional):_________________.
3. Working experience (please tick one):

[ ] Developer; [ ] Main contractor; [ ] Subcontractor;
[ ] Consultant (architect); [ ] Consultant (structural engineer);
[ ] Consultant (project management); [ ] Structural steel fabricator;
[ ] Quantity surveyor; [ ] Others, please specify____.

4. Years of working experience in construction industry: _____ years.
5. How many RC framed projects have you been involved in: _______;
6. How many structural steel projects have you been involved in: _______;

Part B: Information on SS-framed building

Instruction: Please answer the questions based on a completed steel framed building project that you have been involved in.

7. Project name:_______________________.
   Construction completed in (year)________.
8. Type of project: [ ] Residential; [ ] Commercial; [ ] Hotel; [ ] Institute; [ ] Factory or entertainment; [ ] Mixed; [ ] Others, please specify ____.
9. Gross floor area (GFA) of the whole project:________ m^2. GFA that used steel frame:______ m^2.
10. Height of building: ______m (excluding basement);____stories (excluding basement); ____stories (basement).
11. Construction duration for the project: from___ (yyyy/mm) to___(yyyy/mm);
    Construction duration for the foundation: from___(yyyy/mm) to___(yyyy/mm);
    Construction duration for the structural frame: from_________(yyyy/mm) to (yyyy/mm).
12. Contract sum for the whole project: S$____; Contract sum for the structural frame: S$___.
13. Amount of structural materials:

Connection ways of structural steel elements: __%_ Welding; __% Bolt

Material amount (including beams, columns and slabs)	Steel frame	
	Structural Steel (ton)	Welding rod (ton)
Super-structure		

Steel imported from: __ton from China; __ton from__ (country name).

14. Consumption of manpower:

Works		**Manpower (manday)**
Form works		
Structural steel frame installation		
Scaffold		
Prefabrication		
Others (please state)		
Total		

15. Costs of machinery:

Machinery		Rental (S$/month)	______set* _____months	
			For whole project	For structural frame
Crane1(__ton)				
Crane2(___ ton)				
Crane3 (tower crane)				
Cutting				
Others (please state)				
Total				

16. Contingency cost (if any): S$______.

17. Type of fire protection system used in this project:________.

Cost of fire protection system: S$_______.

18. Type of structural steel anti-corrosion system used in this project:_____ .

Cost of anti-corrosion system: S$_________. For this project, the anti-corrosion systems have a life expectancy of ____years.

19. Amount of reused structural steel elements for this project:______ton.

20. The waste rate of steel (on-site construction):___%; the waste rate of steel (in prefabricator factory):__%; the waste rate of steel (demolish):_%.

21. Energy consumption of the project:

Energy consumption	Diesel consumption (l)	Electricity from power grid (kwh)	Gasoline (l)
Total energy consumption for all construction processes (including the architectural stage)			
Energy consumption for structural construction (please estimate the amount or the percentage of the total)			

Accommodation of labors: [ ] on site; [ ] not on site

22. The extent of noise produced during the structural frame construction processes:

[ ] extremely unsatisfactory [ ] unsatisfactory [ ] neutral [ ] good [ ] outstanding

23. Water consumption during the structural frame construction processes: ___________m^3.

24. Accident Severity Rate (ASR) of this project:________.

25. The CONQUAS score (structural) achieved by this project:____ .

End of survey.

Thank you for your participation in responding to this questionnaire.

All information will be kept strictly confidential.

Appendix 3: Questionnaire for designers and developers

Letter to participants

National University of Singapore, Department of Building

Interview on Decision Support System for Selection of Structural Frame Material to Achieve Sustainability

Dear Sir/Madam,

I am conducting a research to study the selection of optimal structural frame material for building projects in Singapore. This study involves a survey and your participation is very much needed and appreciated because of your deep knowledge in economic performance, environmental sustainability, and constructability performance of buildings.

I would be grateful if you could grant me a one hour interview. The purposes are to seek your advice on a steel framed building and/or RC framed building.

There is no commercial interest involved in this study. All information we obtain will be treated as confidential and used solely for the purpose of research.

If you would like a summary of the research findings, this can be made available to you. If you have any queries, please do not hesitate to contact me at Tel No: 90271876 or email to g0700345@nus.edu.sg .

I am grateful for your co-operation and hope to hear from you.

Thank you very much for your help.

Your sincerely

Zhong Yun

Ph.D. Candidate

Instruction: Please answer the questions by putting a "√" or filling in the blanks.

Part A: General information

1. Your name (Optional):_____ .
2. Company Name (Optional):________________.
3. Working experience (please tick one):

[ ] Developer; [ ] Main contractor; [ ] Subcontractor;

[ ] Consultant (architect); [ ] Consultant (structural engineer);

[ ] Consultant (project management); [ ] Structural steel fabricator;

[ ] Quantity surveyor; [ ] Others, please specify____.

4. Years of working experience in construction industry: _____ years.
5. How many RC framed projects have you been involved in: _______;
6. How many structural steel projects have you been involved in: _______;

Part B: Information on project

7. Project name: __________________________.
8. Name of developer: ______________________.
9. Name of main contractor: _________________.
10. Estimated design fee for this project: S$______.
11. Please estimate the proportion of loan of the total cost___% and average loan period is____yr(s) (please check with client or refer a client).
12. Please estimate the proportion of sectional area of columns over the GFA of a standard level____%.
13. Please rate the flexibility of internal area use achieved through the design of a structural frame by ticking your responses using the 5-point scale (1 is "extremely unsatisfactory", 2 is "unsatisfactory", 3 is "neutral", 4 is "good", and 5 is "outstanding"): _____.

Part C: The importance of each criterion and attribute

14. Please rate the priority level of the following parameters when you suggest a structural frame using scale1-5 (1 means not important, 5 means very important).

Criteria and attributes	**Priority** (Scale 1-5)
EC: Economic sustainability	
EC1: Structural costs (including costs of materials, machinery, manpower and so on.)	
EC2: Maintenance costs (fire protection, corrosion protection) in operation stage	
EC3: Non-construction costs	
EC3.1: Financial cost	
EC3.2: Taxes	
EC4: Disposal and demolition costs at the end of building's life	
EC5: Potential incomes earned by structural materials	
EC5.1: Increased area by optimizing structural frame (like smaller beams and columns)	
EC5.2: Flexibility of utilizing internal space	
EC5.3: Incentives that client might obtain from government	
EN: Environmental sustainability	
EN1: Material reduction such as by using recycle materials and/or reuse structural elements	
EN1.1: Material recycling rate	
EN1.2: Material reuse rate	
EN1.3:Material recyclability (the potential that the structural materials can be recycled for future use)	
EN1.4: Material reusability (the potential that the structural materials can be reused for next project)	
EN1.5: Material waste rate on site	
EN2: CO_2 emissions/ energy consumption during construction	
EN3: Water consumption during construction	
EN4: Noise pollution during construction	
CP: Constructability	
CP1: Labor saving during construction	
CP2: Construction duration	
CP3: Construction safety	

CP4: Construction quality	
Others (please state and rate):	

15. Please rate the importance level of each factor when you suggest a structural frame to clients by ticking the extent of relative importance shown in the table below.

In this table, each element in the left-hand column (X) is compared against one another in the right-hand column (Y) using a 9-point scale. The definition of intensity of importance is: 1 = "equal importance", 3 = "weak importance of one over another", 5 = "essential or strong importance", 7 = "demonstrated importance", 9 = "absolute importance", and 2, 4, 6, and 8 are intermediate values between two adjacent judgments.

<table>
<tr><th rowspan="3">X</th><th colspan="17">Importance</th><th rowspan="3">Y</th></tr>
<tr><th colspan="8">X is more important
extremely ←</th><th>equal
importance</th><th colspan="8">Y is more important
extremely →</th></tr>
<tr><th>9</th><th>8</th><th>7</th><th>6</th><th>5</th><th>4</th><th>3</th><th>2</th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th></tr>
<tr><td>Economic sustainability</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Environmental sustainability</td></tr>
<tr><td>Economic sustainability</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Constructability</td></tr>
<tr><td>Environmental sustainability</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>Constructability</td></tr>
</table>

End of survey.

Thank you for your participation in responding to this questionnaire.

All information will be kept strictly confidential.

Appendix 4: Questionnaire for demolition contractors

Letter to participants

National University of Singapore, Department of Building

Interview on Decision Support System for Selection of Structural Frame Material to Achieve Sustainability

Dear Sir/Madam,

I am conducting research to study the selection of optimal structural frame materials for building projects in Singapore. This study involves a survey, and your participation is very much needed and appreciated because of your deep knowledge in terms of the economic and environmental performance of buildings during the demolition stage.

I would be grateful if you could grant me a one-hour interview. The purpose is to seek your advice on a demolished RC-framed building completed within the past 3 years.

There is no commercial interest involved in this study. All information we obtain will be treated as confidential and used solely for the purposes of research.

A summary of the research findings can be made available to you if you like. If you have any queries, please do not hesitate to contact me at Tel No: 90271876 or email g0700345@nus.edu.sg.

I am grateful for your cooperation and hope to hear from you.

Thank you very much for your help.

Yours sincerely,

Zhong Yun

Ph.D. candidate

Instructions: Please answer the questions by putting a "√" or filling in the blanks.

1. Your name (Optional):_______________.

2. Company Name (Optional):___________.

3. Years of work experience in building industry:

[ ] Less than 3 years; [ ] 3~5 years; [ ] 5~7 years; [ ] More than 7 years

4. What kind of demolition method is used to demolish RC-framed buildings?

[ ] Hand demolition; [ ] Pusher arm demolition; [ ] Deliberate collapse demolition;

[ ] Demolition ball techniques; [ ] Wired rope pulling demolition;

[ ] Demolition by explosives; [ ] Other, please specify __________.

5. The price for demolishing RC-framed buildings:____S$/m^2.

6. The average price for selling the following demolished materials:

Usages	Reinforcement bars (S$ per ton)	Steel columns and beams (S$ per ton)	Concrete (S$ per ton)
For direct reuse			
For recycling			
Others			

7. Please indicate the proportion of the following demolished materials that can be reused and recycled:

Usages	Reinforcement bars (%)	Steel columns and beams (%)	Concrete (%)
For direct reuse			
For recycling			
Others			

End of survey.

Thank you for your participation in responding to this questionnaire.

All information will be kept strictly confidential.

Appendix 5: DSSSSM

Appendix 5.1: Weighting system

1. Please check if you agree with the importance of each factor in column X compared to the factor in column Y when you select a structural frame.

   In this table, each element on the left side (X) is compared against one another on the right side (Y) using a 9-point scale. (1 means “equal importance”, 3 means “weak importance of one over another”, 5 means “essential or strong importance”, 9 means “absolute importance”, and 2, 4, 6, and 8 mean intermediate values between two adjacent judgments).

   If you agree, please go to question 2. If you do not agree, please delete the original numbers and type the number of your valuation into the corresponding block of the table below.

X	Importance																	Y
	X is more important extremely ←								equal importan	→ Y is more important extremely								
	9	8	7	6	5	4	3	2	1	2	3	4	5	6	7	8	9	
Economic sustainability							2.97											Environmental sustainability
Economic sustainability								1.43										Constructability
Environmental sustainability											2.49							Constructability

2. Please check if you agree with the importance of each criterion and attribute when you select a structural frame. In this table, a 5-point scale is used to evaluate the importance (1 means not important, 5 means very important).

   If you agree, please go to the next sheet named 'rating'. If you do not agree, please replace the original numbers by typing the number of your valuation into the shaded blocks.

Criteria and attributes	Importance (Scale 1-5)
Factor 1: Economic sustainability	
EC1: Structural costs (including costs of materials, machinery, manpower and so on.)	4.39
EC2: Maintenance costs (fire protection, corrosion protection) in operation stage	3.31
EC3: Non-construction costs (financial costs and taxes)	3.31
EC5: Potential incomes earned by structural materials	3.00
EC5.1: Increased area by optimizing structural frame (like smaller beams and columns)	*3.26*
EC5.2: Flexibility of utilizing internal space	*3.10*
Factor 2: Environmental sustainability	
EN1: Material reduction such as by using recycle materials and/or reused structural elements	3.18
EN1.1: Material recycling rate	3.13
EN1.3:Material recyclability (the potential that the structural materials can be recycled for future use)	*2.72*
EN1.5: Material waste rate on site	*2.80*
EN2: CO_2 emissions/ energy consumption during construction	2.31
EN3: Water consumption during construction	2.85
Factor 3: Constructability	
CP1: Labor saving during construction	3.95
CP2: Construction duration	4.51
CP4: Construction quality	4.33

3. Weights of factors

A	EC	EN	CP
EC	1.00	2.97	1.43
EN	0.34	1.00	0.40
CP	0.70	2.49	1.00
Sum	2.04	6.46	2.83

4. Weights of factors, criteria, and attributes

<table>
<tr><th></th><th>Importance</th><th>ωi</th><th>ωij</th><th>ωijn</th></tr>
<tr><td>EC1</td><td>4.385</td><td rowspan="6">0.485</td><td>0.313</td><td></td></tr>
<tr><td>EC2</td><td>3.308</td><td>0.236</td><td></td></tr>
<tr><td>EC3</td><td>3.308</td><td>0.236</td><td></td></tr>
<tr><td>EC5</td><td>3.000</td><td rowspan="3">0.214</td><td></td></tr>
<tr><td>EC5.1</td><td>3.256</td><td>0.512</td></tr>
<tr><td>EC5.2</td><td>3.103</td><td>0.488</td></tr>
<tr><td>EN1</td><td>3.179</td><td rowspan="6">0.154</td><td rowspan="4">0.528</td><td></td></tr>
<tr><td>EN1.1</td><td>3.128</td><td>0.362</td></tr>
<tr><td>EN1.3</td><td>2.718</td><td>0.315</td></tr>
<tr><td>EN1.5</td><td>2.795</td><td>0.323</td></tr>
<tr><td>EN2</td><td>0</td><td>0.000</td><td></td></tr>
<tr><td>EN3</td><td>2.846</td><td>0.472</td><td></td></tr>
<tr><td>CP1</td><td>3.949</td><td rowspan="3">0.361</td><td>0.309</td><td></td></tr>
<tr><td>CP2</td><td>4.513</td><td>0.353</td><td></td></tr>
<tr><td>CP4</td><td>4.333</td><td>0.339</td><td></td></tr>
</table>

Appendix 5.2: Rating system

1. Rating for proposed RC frame

Please estimate the performance value for measurement in the shaded boxes. Then type your estimation into the corresponding blocks to replace the original numbers. If you are not sure about your estimation on one or several measurements, just leave the information already input.

RC frame		Measurement	Performance value	Rating
Project information - Total Gross Floor Area (GFA)		m^2		
1	**Factor1: Economical sustainability(EC)**			
1.1	Criterion 1.1: Structural cost (EC1)	Unit structural cost (S$/$m^2$)	758.60	54.72
1.2	Criterion 1.2: Maintenance cost (EC2)	NA	NA	100.00
1.3	Criterion 1.3: Non-construction cost (EC3)			
1.3.1	*Financial costs(EC3.1)*	Unit cost (S$/$m^2$)	10.79	59.44
		Proportion of loan (%)		
		Loan period (years)		
		Interest rate (%)		
1.4	Criterion 1.4: Additional incomes (EC5)			
1.4.1	*Additional usable area (EC5.1)*	Sectional area of columns / GFA of a standard level (%)	2.55	45.83
1.4.2	*Flexibility of utilizing internal area(EC5.2)*	1 = "unsatisfactory" 2 = "satisfactory" 3 = "neutral" 4 = "very good" 5 = "outstanding"	4	75.00
2	**Factor2: Environmental sustainability(EN)**			
2.1	Criterion 2.1:Material consumption (EN1)			
2.1.1	*Recycling rate (EN1.1)*	(%)	22.93	41.77
		Amount of reinforced rebar consumption (ton)		
		Steel price (S$/ton)		
		Amount of Concrete consumption (m3)		
		Mixed concrete price (S$/$m^3$)		
2.1.2	*Recyclability (EN1.3)*	Proportion of recyclable structural material in the end of life stage (%)	85.00	50.00

2.1.3	*Waste rate (EN1.5)*	Percentage of wasted material against total material consumption (%)	6.00	41.67
2.2	Criterion 2.2: CO_2 emission (EN2)	(kg/m^2)	24.40	44.47
		Electricity consumption for structure construction (kg/kwh)		
		Diesel consumption for structure construction (l)		
		Gasoline consumption for structure construction (l)		
2.3	Criterion 2.3: Water consumption (EN3)	Water consumption / Total GFA (l/m^2)	1143.25	36.52
		Water consumption for structural construction (tonnes)		
3	**Factor 3: Constructability Performance(CP)**			
3.1	Criterion 3.1: Labor consumption (CP1)	Amount of labor consumption / Total GFA ($Manday/m^2$)	1.47	46.23
		Labor consumption for structural construction (Manday)		
3.2	Criterion 3.2: Construction duration (CP2)	Duration of structural construction *1000/Total GFA ($Day/1000m^2$)	14.01	48.49
		Duration for structural construction (Months)		
3.3	Criterion 3.3: Construction quality (CP4)	CONQUAS score	90.10	35.16

2. Rating for proposed SS frame

Please estimate the performance value for measurement in the shaded boxes. Then type your estimation into the corresponding blocks to replace the original numbers. If you are not sure about your estimation on one or several measurements, just leave the information already input.

SS frame		Measurement	Performance value	Rating
Project information - Total Gross Floor Area (GFA)		m^2		
1	**Factor1: Economical sustainability(EC)**			
1.1	Criterion 1.1: Structural cost (EC1)	Unit structural cost (S$/m2)	1055.80	30.05
1.2	Criterion 1.2: Maintenance cost (EC2)	NA		0.00
1.3	Criterion 1.3: Non-construction cost (EC3)			
1.3.1	*Financial costs(EC3.1)*	Unit cost (S$/$m^2$)	59.06	22.16
		Proportion of loan (%)		
		Loan period (years)		
		Interest rate (%)		
1.4	Criterion 1.4: Additional incomes (EC5)			
1.4.1	Additional usable area (EC5.1)	Sectional area of columns / GFA of a standard level (%)	1.70	90.00
1.4.2	Flexibility of utilizing internal space (EC5.2)	1 = "unsatisfactory" 2 = "satisfactory" 3 = "neutral" 4 = "very good" 5 = "outstanding"	5	100.00
2	**Factor2: Environmental sustainability(EN)**			
2.1	Criterion 2.1:Mateiral consumption (EN1)			
2.1.1	*Recycling rate (EN1.1)*	(%)	39.57	93.03
		Percentage of recycled steel being used for SS prefabrication (%)		
2.1.2	*Recyclability (EN1.3)*	Proportion of recyclable structural material in the end of life stage (%)	98	92.86
2.1.3	*Waste rate (EN1.5)*	Percentage of wasted material against total material consumption (%)	3.00	78.57
2.2	Criterion 2.2: CO_2 emission (EN2)		1.70	86.21
		Electricity consumption for structure construction (kg/kwh)		

		Diesel consumption for structure construction (l)		
		Gasoline consumption for structure construction (l)		
2.3	Criterion 2.3: Water consumption (EN3)	Water consumption / Total GFA (l/m2)	0.20	99.96
		Water consumption for structural construction (Tonnes)		
3	**Factor 3: Constructability Performance(CP)**			
3.1	Criterion 3.1: Labor consumption (CP1)	Amount of labor consumption / Total GFA (Manday/m2)	1.04	73.38
		Labor consumption for structural construction (Manday)		
3.2	Criterion 3.2: Construction duration (CP2)	Duration of structural construction *1000/Total GFA (Day/1000m2)	11.33	57.40
		Duration for structural construction (Months)		
3.3	Criterion 3.3: Construction quality (CP4)	CONQUAS score	97.00	83.33

Appendix 5.3: Aggregation

3. Aggregate score calculation for proposed RC frame

RC	ω_{ijn}	r_{ijn}	$\omega_{ijn} * r_{ijn}$	ω_{ij}	r_{ij}	$\omega_{ij} * r_{ij}$	ω_i	r_j	SSM
EC							0.48	67.68	54.70
EC1				0.31	54.72	17.14			
EC2				0.24	100.00	23.63			
EC3				0.24	59.44	14.04			
EC5				0.21	60.07	12.87			
EC5.1	0.51	45.83	23.47						
EC5.2	0.49	75.00	36.60						
EN							0.15	40.64	
EN1				0.53	44.32	23.39			
EN1.1	0.36	41.77	15.12						
EN1.3	0.31	50.00	15.73						
EN1.5	0.32	41.67	13.48						
EN2				0.00	44.47	0.00			
EN3				0.47	36.52	17.25			
CP							0.36	43.28	
CP1				0.31	46.23	14.27			
CP2				0.35	48.49	17.10			
CP4				0.34	35.16	11.91			

4. Aggregate score calculation for proposed SS frame

SS	ω_{ijn}	r_{ijn}	$\omega_{ijn} * r_{ijn}$	ω_{ij}	r_{ij}	$\omega_{ij} * r_{ij}$	ω_i	r_j	SSM
EC							0.48	34.98	57.08
EC1				0.31	30.05	9.41			
EC2				0.24	0.00	0.00			
EC3				0.24	22.16	5.24			
EC5				0.21	94.88	20.33			
EC5.1	0.51	90.00	46.08						
EC5.2	0.49	100.00	48.80						
EN							0.15	93.81	
EN1				0.53	88.30	46.59			
EN1.1	0.36	93.03	33.68						
EN1.3	0.31	92.86	29.21						
EN1.5	0.32	78.57	25.41						
EN2				0.00	86.21	0.00			
EN3				0.47	99.96	47.22			
CP							0.36	71.11	
CP1				0.31	73.38	22.65			
CP2				0.35	57.40	20.24			
CP4				0.34	83.33	28.22			

5. Conclusion: _____ frame is recommended